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Interactive Cooling System

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Indiana University Purdue University - Fort Wayne

Department of Engineering



ENGR 410 - 411

Capstone Senior Design Project

Report #2

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Abstract & Summary

Parker Hannifin's Precision Cooling Business Unit has sponsored the following capstone senior design project for five Indiana University Purdue University – Fort Wayne engineering students. The purpose of this project is to create an Interactive Cooling System (ICS) that demonstrates the versatility and capabilities of Parker's Precision Cooling two-phase cooling technology. The two-phase cooling technology utilizes the heat of vaporization of a refrigerant in order to absorb excessive heat, commonly generated by a higher powered electronic. The two-phase cooling technology is safer and more efficient method of heat transfer that reduces the weight, increases power density, and costs far less than the traditional heat sink or water cooling system.

The ICS is composed of the following components: cold plate, condenser, fan, pump, accumulator, piping, pressure sensors, temperature sensors, flow meter, R-134A refrigerant, fiberglass shell, aluminum frame, power supply, personal computer (PC), touchscreen monitor, data acquisition system (DAQ), and control algorithm. These components were researched, analyzed, modeled and selected to achieve specific performance criteria that are detailed further in Fall 2010 semester's report (Report 1). The phase composition of the refrigerant at the exit of the cold plate was required to be no greater than 70% gas. The maximum weight of the display was set at 500 lbs. The display must fit through a common three foot by seven foot door. The exterior of the display is safe to the touch. The ICS should dissipate heat loads from 100 to 1000 W. The ICS will achieve a specified desired temperature to within 1°C of the user input.

The fiberglass display cabinet was designed and fabricated to match a computer-aided design (CAD) model. A negative of this model was computer numerical controlled (CNC) machined to create a mold to fabricate the fiberglass shell. This was secured onto a custom designed aluminum frame that was fabricated at Parker. The condenser, pump and fan were selected and purchased. The cold plate, cold plate housing, pump cover, and pump manifold were machined off-site. The fan-to-condenser shroud and piping assemblies were designed, assembled, and brazed at Parker. A testing rig was made in advance to hold all the two-phase cooling cycle during final brazing and leak testing. Electrical wiring consisted of distributing power from the power entry module to the 24VDC power supply, the DAQ, the PC, the touch-screen, and the DIN-A-MITE heater controller. Low-voltage wiring had to be distributed from the 24VDC power supply to the pump, fan and sensors. The DAQ was initialized and programmed with the control algorithm and the graphical user interface (GUI) designed with Parker's InteractX 3.0 MachineShop.

Tests were conducted in order to develop empirical relationships between the heat source temperature and fan speed in order to develop a control algorithm (working condition test). After the control algorithm was in place, tests were conducted in order to see how quickly and accurately the heat source temperature reached the desired temperature (control systems operation test). An ease of operation test was conducted in order to qualitatively assess the GUI.

Testing revealed that the phase composition of the refrigerant is held at a steady-state quality of no greater than 0.7. The maximum weight of the display is less than 500 lb. The display fits through a common 3'x7' door. The exterior of the display unit is safe to the touch. The ICS is able to dissipate heat loads from 100 to 1000 W. The ICS is able to hold a specific desired temperature to within 1°C of the user input.

In general the goals set out at the beginning of the project were either met or exceeded. Future testing should be done in order to design a controller that is able to handle the transient effects from switching from a higher heat load to a lower heat load.

Section I:

Detailed Conceptual Design

THERMODYNAMIC ANALYSIS

Variables, descriptions, and units to aid in the discussion of the thermodynamic analysis are summarized in Table 1.

Table 1 – Variables, Descriptions, and Units

Variable	Description	Value/Units
\dot{Q}	Heat from Source	[kW]
T_{source}	Controlled Source Temperature	[°C]
T_1	State 1 Temperature	[°C]
$T_{air-out}$	Temp. of Air at Condenser Output	[°C]
T_{air-in}	Ambient Air Temperature	[°C]
h_1	Enthalpy at State 1	[kJ/kg]
h_2	Enthalpy at State 2	[kJ/kg]
h_3	Enthalpy at State 3	[kJ/kg]
\dot{m}_{R134a}	Mass Flow Rate of R134a	[kg/s]
\dot{m}_{air}	Mass Flow Rate of Condenser Air	[kg/s]
R_{eq}	Thermal Resistance of Cold Plate	[°C/kW]
c_p	Specific Heat of Air	[kJ/kg·K]

To properly control the ICS, the thermodynamic system was analyzed completely. This analysis was required to properly size and select components such as the heat exchanger, the pump, the cold plate, and the fan. The control system will utilize the following thermodynamic analysis to control the temperature of the heat source. Figure 1 shows a schematic of the thermodynamic cycle.

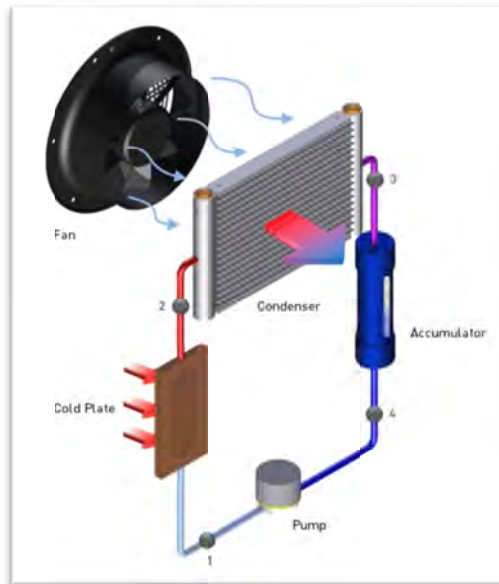


Figure 1 - Thermodynamic Schematic of Two-Phase Cooling Technology

VARIABLES, INITIAL CONDITIONS, AND ASSUMPTIONS

There are several initial conditions and assumptions that must be made to properly analyze the thermodynamics of the system. The first assumption that must be made is the thermal resistance of the cold plate. Since the designed cold plate is similar to other cold plates that Parker uses, the thermal resistance can be assumed to be the same. Typical Parker cold plates that work with R134a refrigerant in two-phase cooling have a thermal resistance of 30 [$^{\circ}\text{C}/\text{kW}$].

A key assumption that must be made in the ICS thermodynamic system is phase-state of the entering refrigerant. The R-134a refrigerant must be in a saturated liquid state or sub-cooled when it enters the cold plate. For simplicity, it will be considered a saturated liquid. In the problem statement, as detailed in Report 1 from Fall 2010, stated that the refrigerant should be about 70% vapor, by mass, as it leaves the cold plate. Therefore, it can be assumed the quality of the R-134a is 0.70 at the exit of the cold plate. It can be assumed the refrigerant at the exit of the condenser will be a saturated liquid.

For simplicity, it can be assumed that there are no heat losses or pressure drops in the copper pipes. However, there will be a significant pressure drop that occurs in the condenser. It will be assumed that the pressure drop that occurs in the condenser is 80 [kPa], which is typical in other Parker systems that are similar to the ICS.

Since the ICS system will only operate indoors, it can be assumed that the ambient temperature of the air is 22°C. It can be assumed that at steady state, the air condenser ejects an identical amount of heat from the system as the heat source adds to the system, which is a conservative assumption. It can also be assumed that all of the heat that is generated by the heat source is transferred through the cold plate and then into the refrigerant.

DETERMINING THE FLOW RATE OF THE REFRIGERANT

The first part of the thermodynamic analysis to aid the control system is the flow rate of the refrigerant. When the cycle is started, a user will input a heat load. The system will recognize this load and will set the refrigerant's mass flow rate to a specific value. This value is determined by an energy balance equation over the cold plate.

First, the desired temperature of the refrigerant at State 1 must be calculated. This temperature is dependent on the controlled temperature (input temperature) of the heat source and the heat load. The desired temperature of the refrigerant is determined from Equation 1.

$$\dot{Q} = \frac{T_{source} - T_1}{R_{eq}} \quad (1)$$

Pressure and temperature sensors at State 1 will measure thermodynamic data before the refrigerant travels into the cold plate. The refrigerant at State 2 is a mixture of liquid and vapor refrigerant with a quality of 0.7 and has the same temperature and pressure as State 1. Using thermodynamic tables, the enthalpy of each of these states can be determined. Since it is assumed that the heat out of the source is equal to the heat transferred to the refrigerant over the cold plate, Equation 2 can be used to determine the mass flow rate of the fluid. The pump speed will be adjusted so that the refrigerant will flow at this rate. After the pump speed is adjusted, it will constantly provide this flow rate until the user changes the heat-load input.

$$\dot{Q} = \dot{m}_{R134a} \cdot (h_2 - h_1) \quad (2)$$

DETERMINING THE FAN SPEED

The rest of the thermodynamic analysis aids the controller by determining and adjusting the fan speed to properly cool the ICS. With State 2 known, State 3 was analyzed under ideal running conditions; the refrigerant should be a saturated liquid at this state. It also was assumed that the pressure drop in the condenser was equal to 80 kPa. Using these two properties, the temperature and enthalpy of the refrigerant were determined from published thermodynamic tables.

Since the enthalpies of State 2 and State 3 are known, as well as the flow rate of the refrigerant inside the condenser, Equation 3 can be utilized to determine the flow rate of the air.

$$\dot{m}_{R134a} \cdot (h_2 - h_3) = \dot{m}_{air} \cdot c_p (T_{air-out} - T_{air-in}) \quad (3)$$

While the Equation 3 holds valid, it does now allow a solution of the mass flow rate of the air, because the temperature of the air leaving the condenser is also unknown.

Since the refrigerant flow rate is pre-determined, the values may have to be interpolated from the condenser data. Once the flow rate is determined, the values of the air flow rate and the leaving temperature must be adjusted until Equation 3 becomes balanced. This will give an initial air-flow rate to communicate to the fan. The controller will monitor the temperature of the cold plate and other thermodynamic properties of the system. If the system does not become steady with the characteristics that match the thermodynamic model, the controller will adjust the fan speed until the system is running properly.

OTHER CONSIDERATIONS

The highest pressure in the system will occur at the outlet of the pump, which is at State 1. Since the temperature and the quality of State 1 are both known, the pressure can be determined from published thermodynamic tables. The system will be designed to withstand this pressure (with a high safety factor) at the highest heat load that the source will provide. This maximum pressure is approximately 2,000 kPa.

FEA ANALYSIS

In the ICS, the copper cold plate is the device that exchanges heat from the heat source to the fluid (refrigerant). The cold plate is mounted directly to the heat source. Thermal grease is applied between the cold plate and heat source to reduce the contact thermal resistance. A custom cold plate was designed by the team for the ICS.

The first characteristic of the cold plate that was determined was the overall size. In the current Cool Cube, the cold plate is large enough to remove the necessary amount of heat from the source, but it is not large enough adequately display the phase-change of the refrigerant. Therefore, the team decided to design a larger cold plate to use on the ICS. The overall dimensions were selected to be 0.18 m (7 in.) by 0.09 m (3.5 in.).

After the overall dimensions were selected, the flow cavity was designed. The flow cavity consists of an inlet and outlet orifice, flow distributors, and micro-channels. The purpose of the flow distributors is to equally distribute the refrigerant to the micro-channels so that the flow through the channels is uniform. The flow distributors were optimized for uniform flow by using a trial and error method. The model was adjusted using SolidWorks software until a uniform flow through the channels was accomplished. The analysis was performed using the FEA simulation tools included in SolidWorks.

After the flow distributors were designed, the channel layout was designed. Since the channels needed to be large enough to easily view the flow of the refrigerant and the evaporation, it was determined that the cold plate should contain no more than 30 channels. Three different channel layouts were compared using FEA. The first layout contained 10 channels, the second contained 20 channels, and the third contained 30 channels. Using ANSYS software, the thermal resistance of the cold plate was determined for each of these cases using two different convective heat transfer coefficients. The values of these convective heat transfer coefficients were selected based on a range of published values for boiling refrigerant. Table 2 shows the results of the FEA.

Table 2 – FEA Results of Channel Optimization

n (channels)	Q [W]	h=1,500 W/m ² ·K			h=100,000 W/m ² ·K		
		T _{max} [°C]	T _{refrig} [°C]	R _{eq} [°C/W]	T _{max} [°C]	T _{refrig} [°C]	R _{eq} [°C/W]
10	1000	79.6	50.0	0.030	80.4	75.0	0.0054
10	500	79.8	65.0	0.030	80.2	77.5	0.0054
10	100	80.0	77.0	0.030	80.0	79.5	0.0050
20	1000	79.5	56.0	0.024	80.0	74.6	0.0054
20	500	79.8	68.0	0.024	80.0	77.3	0.0054
20	100	80.0	77.6	0.024	80.0	79.5	0.0054
30	1000	80.0	59.5	0.021	80.0	74.6	0.0054
30	500	80.0	69.8	0.021	80.0	77.3	0.0054
30	100	80.0	78.0	0.021	80.0	79.5	0.0050

After performing the analysis, it was determined that a cold plate with 30 channels was the most effective, and therefore would be used in the ICS. It is known from previous research at Parker that the actual thermal resistance is similar to the results obtained when using a convective heat transfer coefficient of 1,500 [W/m²·K]; therefore, this coefficient was used in other simulations and calculations. Using the ANSYS tools, a temperature distribution was mapped in the cold plate with 30 channels. Figure 2 displays the temperature distribution throughout a cold plate when it is supplied with 1000 [W] of heat.

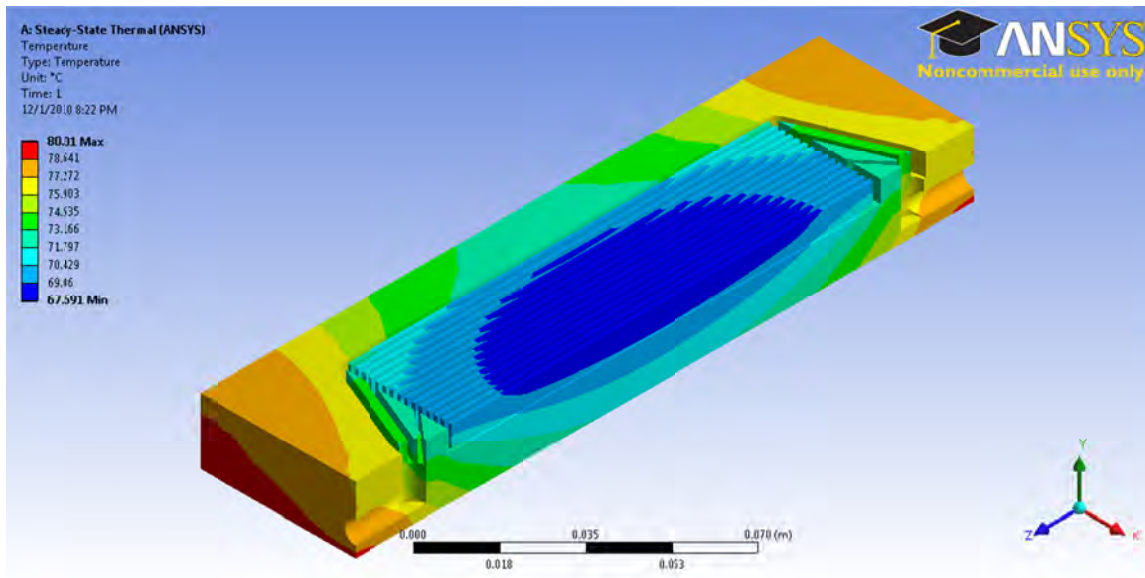


Figure 2 – Temperature Distribution through Cold Plate with 1000 W Heat Supply, T_{refrig} of 50 °C

After selecting a cold plate with 30 channels, the team decided to analyze the pressure drop of the refrigerant throughout the device. ANSYS was used to perform this analysis. Figure 3 displays the results of the pressure distribution throughout the cold plate. The fluid used in the simulation was water that had a flow rate equal to the systems flow rate when 1000 W of heat is supplied. The results of the experiment yielded a maximum pressure drop of about 310 Pa, which should be similar to the maximum pressure drop of the actual system. This pressure drop is adequate for use in the ICS system.

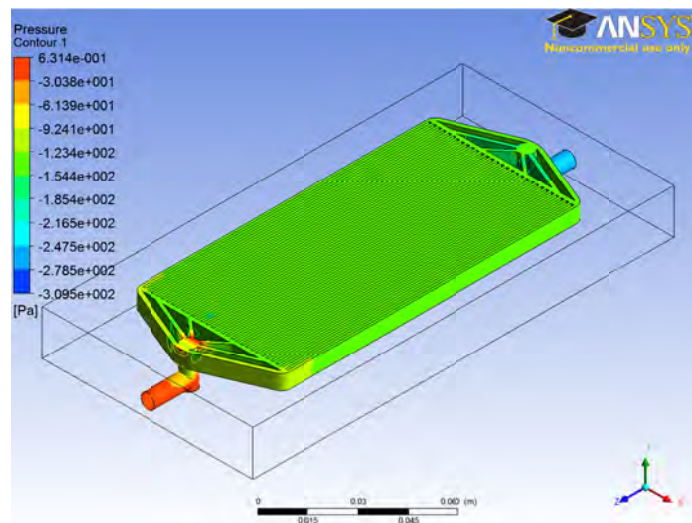


Figure 3 - Pressure Distribution through Cold Plate

See Appendix A-1 for Cold Plate Dimensioned Drawing.

GLASS COVERING

The sight glass covering for the cold plate is made of tempered borosilicate glass. The thickness of glass for the ICS unit will be 1". The size will match the 3.5" by 7" dimensions of the cold plate. John C. Ernst, the manufacturing company of the glass, provides a chart to assist in ordering the proper thickness of glass to withstand the pressure of the working fluid it is displaying and the unsupported length of the glass. A copy of the chart is displayed in Figure 4.

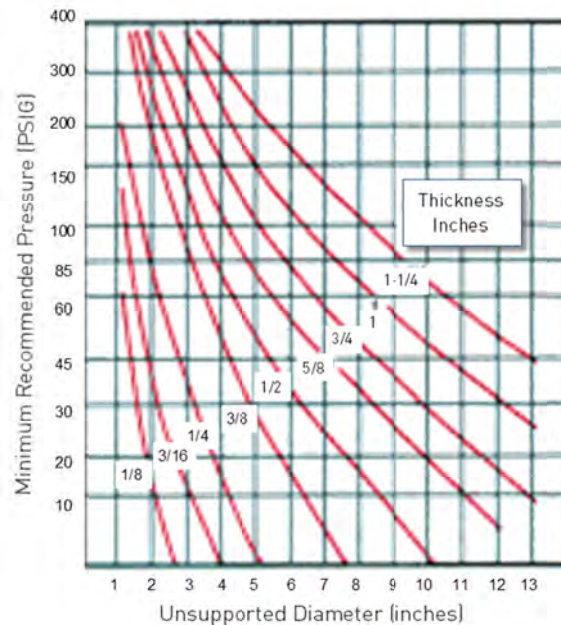


Figure 4 - John C. Ernst Pressure Chart for Sight Glass

For tempered borosilicate glass, the pressure ratings in Figure 4 are increased by 300%. Since the maximum operating pressure of the refrigerant is approximately 2068 kPa (300 PSI), the maximum pressure read from Figure 4 is 100 PSI. The maximum unsupported length is 5.5". Referencing the Figure 4, the minimum thickness of glass is 0.75" thick. To ensure that the potentially dangerous glass does not break, a safety margin is added to this approximation. The cold plate in the ICS will be covered by a 1" thick piece of glass.

MOUNTING

The cold plate and sight glass are sealed together in the ICS using the assembly shown in Figures 5 and 6. An aluminum plate with counter bores squeezes the cold plate to seal directly to the glass by screwing bolts into a machined overlay aluminum cover. The base plate includes mounting holes to secure the assembly to the exterior structure. See Appendix A-2 and A-3 for the aluminum cover and aluminum base detailed drawings, respectively.

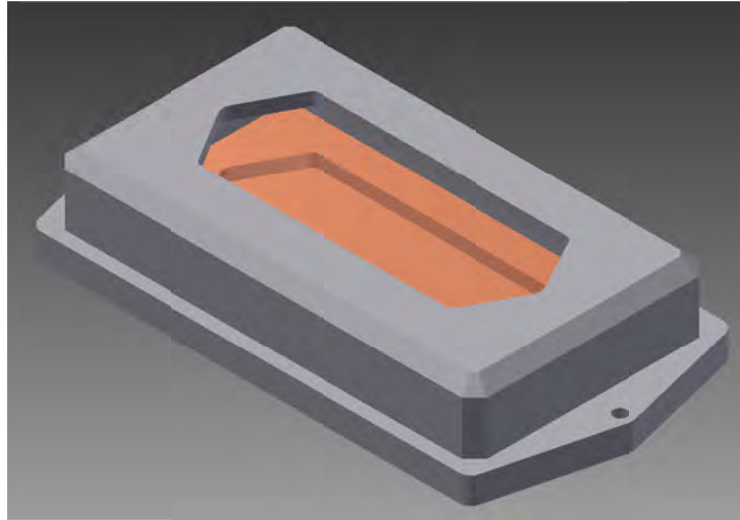


Figure 5 - Cold Plate Assembly

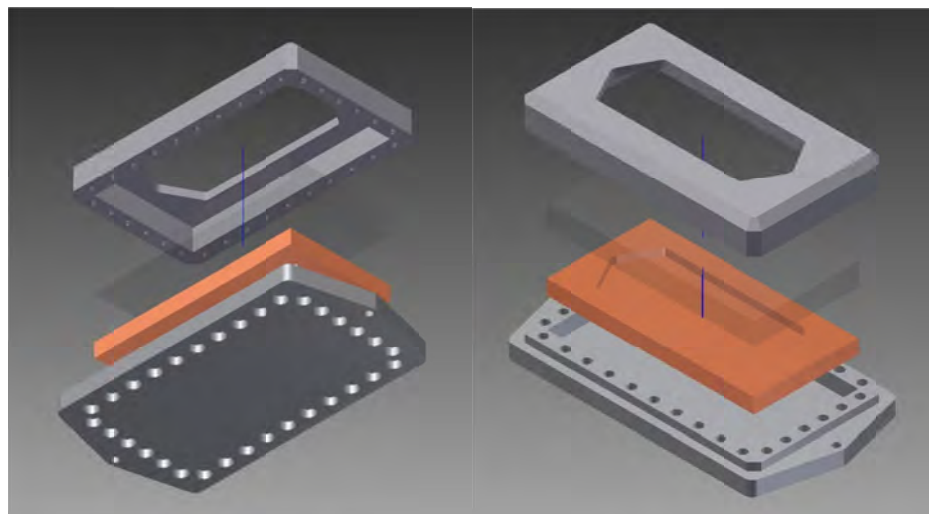


Figure 6 - Two Exploded Cold Plate Assembly Views

CONDENSER

The condenser for the ICS was designed and purchased from Luvata. It is a microchannel design with approximate dimensions of heat transfer area of 8" x 10" with a 1" depth. The condenser has a maximum dissipation of 1,038 W at 370 cfm air flow from the fan and a refrigerant flow rate of 0.84lbm/min. See the Luvata dimensioned drawing in Appendix A-4.

Several trials of the condenser were performed using Luvata's proprietary software. An initial evaluation of the results is shown in Table 3. The delta air temperature is the

change of in temperature between the incoming air temperature and the exiting air temperature.

Table 3 - Condenser Data

		Leaving Air Temperature (C)					Δ Air Temperature (C)		
		Refrigerant Flow Rate (lbm/min)					Refrigerant Flow Rate (lbm/min)		
		0.63	0.84	1.05			0.63	0.84	1.05
Air Flow Rate (cfm)	277.5	29.7	31.0	31.6	Air Flow Rate (cfm)	277.5	5.811	7.111	7.711
	370.0	28.4	29.6	30.5		370.0	4.511	5.711	6.611
	462.5	27.6	28.6	29.5		462.5	3.711	4.711	5.611

HEATER

To create the varying heat loads of the user inputs, a heat sinkable planar resistor (heater) was selected for the ICS. [6] Two 1000 W heaters with 3 inch square surfaces will be adhered to the underneath side of the cold plate using the recommended compound. A variable voltage will be connected to both leads of both heaters to create the effects of heat production from a heat source such as an IGBT, processor, or Silicon Controlled Rectifier (SCR).

PIPE SIZING

The following is an analysis of how the size of the pipes that will be used in the ICS was determined.

Reynolds number can be expressed as the following relationship in Equation 4:

$$Re = \frac{\rho v D}{\mu} \quad (4)$$

where density is ρ , velocity is v , pipe diameter is D , and viscosity is μ .

Mass flow rate is \dot{m} is defined in Equation 5:

$$\dot{m} = \rho Q \quad (5)$$

where volumetric flow rate is Q .

The velocity of the refrigerant is also equal to the following shown in Equation 6:

$$v = \frac{Q}{A} = \frac{4Q}{\pi D^2} = \frac{4\dot{m}}{\rho \pi D^2} \quad (6)$$

where pipe cross-sectional area is A .

Reynolds's number may also be expressed as the following as defined in Equation 7:

$$Re = \frac{4\rho Q}{\mu\pi D} = \frac{4\dot{m}}{\mu\pi D} \quad (7)$$

The Bernoulli's equation relates the pressure drop between any two points in a single-path pipe system (see Equation 8). This is used to calculate the pressure losses from the pump outlet (node 1) throughout the entire refrigerant-cycle piping and back to the pump inlet (node 2).

$$\left(\frac{P_1}{\rho} + \alpha_1 \frac{v_1^2}{2} + gz_1\right) - \left(\frac{P_2}{\rho} + \alpha_2 \frac{v_2^2}{2} + gz_2\right) = \sum h_l + \sum h_{lm} \quad (8)$$

For the ICS, the change in kinetic energy and the change in potential energy throughout the cycle are negligible and the minor losses are also negligible, so the energy balance is reduced to the following as shown in Equation 9:

$$\left(\frac{P_1}{\rho}\right) - \left(\frac{P_2}{\rho}\right) = \sum h_l \quad (9)$$

Each major loss in pressure head is defined in Equation 10:

$$h_l = f \frac{L}{D} \frac{v^2}{2} \quad (10)$$

where the friction factor, f , for turbulent flow (Reynolds number, $Re \geq 2300$) can be approximated as the following non-linear Equation 11:

$$\frac{1}{\sqrt{f}} = -2 \cdot \log \left(\frac{e/D}{3.7} + \frac{2.51}{Re \cdot \sqrt{f}} \right) \quad (11)$$

where e is roughness factor.

Notice that an iterative process has to be used in order to solve for f . So the pressure difference between node 1 and node 2 can be approximated as the following defined in Equation 12:

$$\Delta P = f \frac{L}{D} \frac{\rho}{2} \left(\frac{4Q}{\pi D^2} \right)^2 = \frac{8fL\rho Q^2}{\pi^2 D^5} \quad (12)$$

The maximum pressure head of the pump is approximately 180 kPa at the max flow rate of 428 ml/min. The pressure loss caused by the piping must not exceed 0.1% of the pump head or $\Delta P_{pipe,max} \leq 180 \text{ kPa}$. The iterative process was carried out using the solver

command using Microsoft Excel for various standard pipe sizes at the refrigerant and piping properties summarized in Table 4. This produced the pipe sizing shown in Table 5.

Table 4 - Refrigerant and Piping Properties

Property	Value	Units
T	77.9	°C
μ	0.0001649	kg/m·s
ρ	1155	kg/m ³
Q	1.66667E-05	m ³ /s
e	0.000005	-

Table 5 - Pipe Sizes and Properties

Nominal Pipe Size (in)	Inside diameter (m)	Re	f	Delta P (Pa)
1/8	6.833E-03	9305	0.04016	208.0
1/4	9.246E-03	6876	0.03768	49.1
3/8	1.252E-02	5077	0.03486	11.6
1/2	1.580E-02	4024	0.03255	3.9

As can be seen from Table 5, 1/4" piping is the smallest pipe diameter that meets the pressure drop criteria and that was the chosen size.

PUMP

The ICS will be equipped with a 1000 ml/min pump. The Diener brushless DC motor pump was ordered from the 'smart' series which includes the pump controller integrated into the assembly. From the thermodynamic calculations, the maximum volumetric flow rate is determined to be 427.7 ml/min (7.13E-6 m³/s) Using Figure 7, the available pressure the pump can deliver at 2000 rpm is 1.8 bar (180kPa).

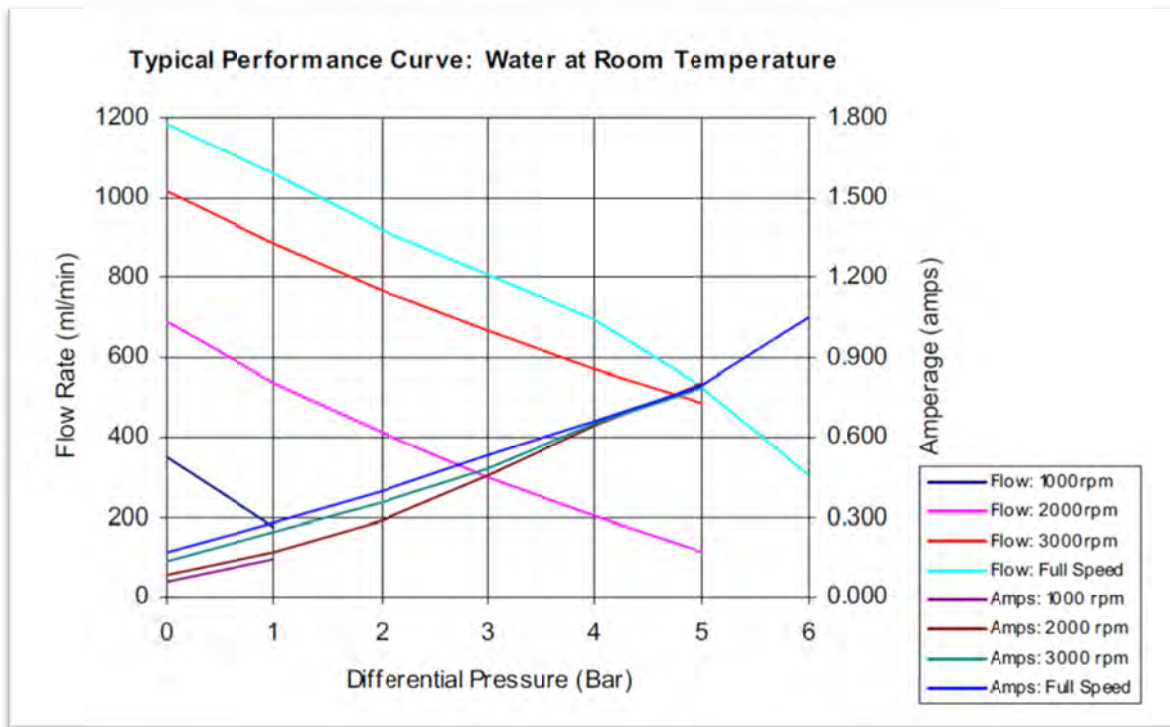


Figure 7 - Performance Curve of Diener Silencer Series Pump [1]

The capacity of the pump was verified after reviewing the maximum pressure drops across the various ICS components included in Table 6. See the custom engraved pump base plate in Appendix A-5.

Table 6-Component Pressure Drops and Gains

Max ΔP Drop Across Condenser (Pa)	2267
Max ΔP Drop Across Cold Plate (Pa)	309
Max ΔP Drop Across Pipe (Pa)	49.1
ΔP Gain Across Pump at Max Flow (Pa)	180,000

FAN

The fan that was selected for the ICS condenser is an EBM-Papst 2214F/2TDHH0 fan. With the data from Luvata, a fan with a volumetric flow rate of 0.175 m³/s (370 ft³/min) is needed to eject 1000 Watts of heat from the system. The fan also needs to have a diameter smaller than the height of the condenser face (8 in.). The selected fan meets both of these requirements.

Table 7 presents the fan's manufacturer-given data. The fan also was required to have the capability to exceed the pressure-drop that will occur in the condenser. According

to Luvata, the condenser’s air-pressure drop as air flows through the fins at the maximum flow rate is 140 Pa. Figure 8 shows that the fan is capable of overcoming this pressure. Figure 9 shows a dimensioned schematic of the fan.

Table 7 - EBM-Papst Fan Data

Part #	m ³ /s	Voltage [DC]	Volt. Range	Power [W]	Noise [dBA]	Max Ambient Temp [°C]	Bearing Type	Features	Wgt. [lbs]
2214F/2TDHH0	0.261	24	16 to 30	54	66	70	Ball	Leads	1.0

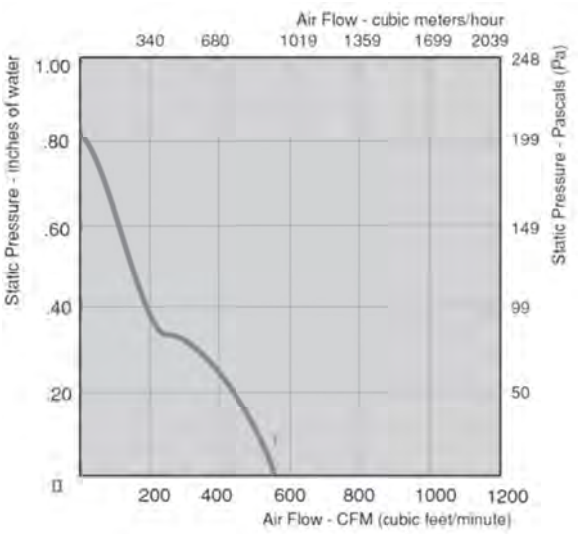


Figure 8 - Manufacturer Pressure-Drop Data [3]

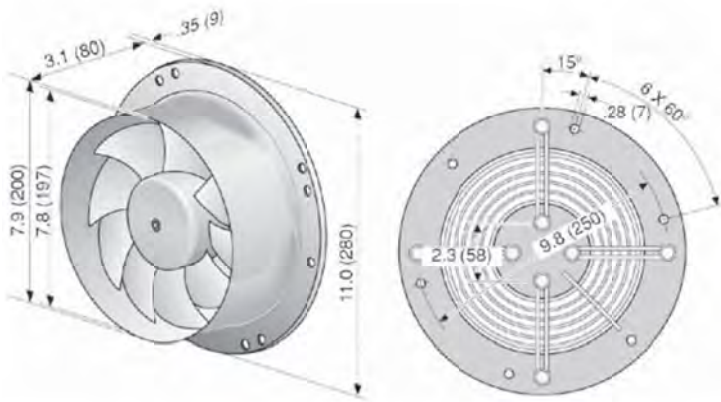


Figure 9 - Dimensioned Schematic of Fan

CONTROL SYSTEM

In the ICS there are two controllers to be designed and implemented. The first controller will set the correct voltage output for the pump in order to maintain a refrigerant quality of less than 0.7 and the second controller will control the voltage output to the fan in order to achieve a desired temperature to be maintained at the cold plate. Two different methods of controlling the fan and the pump were created because their design goals were much different. In the conceptual design stage of the ICS it was decided to use a fuzzy logic controller in order to control the fan. This control method was not the method implemented in the final ICS, because it was difficult to get an accurate model of the system to put in MATLAB/ Simulink. The method that was implemented was similar to a Proportional - Derivative (PD) controller. This controller is a function of heat load and temperature desired.

The pump has a set output for a given heat input whereas the fan must vary with the temperature difference of the cold plate with relation to the desired temperature. These two control methods will be explained as well as a how they were implemented. The controllers were implemented in the same programming language used in the data acquisition process, RSLogix 500. The complete RSLogix 500 program can be seen in Appendix B.

The pump control was designed to maintain a refrigerant quality of less than 0.7. In order to do this, MATLAB was used to generate a table that specifies the correct pump speed in both volumetric and mass flow rates. These two tables can be seen below in Table 8 and Table 9. The MATLAB code used to derive these tables is shown in Appendix C.

Table 8 –Mass Flow Rate

	Mass Flow Rate [kg/s]													
	35 °C	40 °C	45 °C	50 °C	55 °C	60 °C	65 °C	70 °C	75 °C	80 °C	85 °C	90 °C	95 °C	100 °C
100 W	0.0007	0.0008	0.0008	0.0008	0.0008	0.0009	0.0009	0.0010	0.0011	0.0011	0.0013	0.0014	0.0018	0.0027
200 W	0.0015	0.0015	0.0016	0.0016	0.0017	0.0017	0.0018	0.0019	0.0021	0.0022	0.0024	0.0027	0.0033	0.0046
300 W	0.0022	0.0022	0.0023	0.0024	0.0025	0.0026	0.0027	0.0029	0.0030	0.0033	0.0035	0.0039	0.0046	0.0061
400 W	0.0029	0.0030	0.0030	0.0031	0.0033	0.0034	0.0036	0.0038	0.0040	0.0043	0.0046	0.0051	0.0058	0.0073
500 W	0.0036	0.0037	0.0038	0.0039	0.0040	0.0042	0.0044	0.0046	0.0049	0.0052	0.0056	0.0061	0.0070	0.0084
600 W	0.0042	0.0044	0.0045	0.0046	0.0048	0.0050	0.0052	0.0055	0.0058	0.0061	0.0066	0.0071	0.0080	0.0094
700 W	0.0049	0.0050	0.0052	0.0053	0.0055	0.0057	0.0060	0.0063	0.0066	0.0070	0.0075	0.0081	0.0090	0.0104
800 W	0.0056	0.0057	0.0059	0.0060	0.0062	0.0065	0.0067	0.0071	0.0074	0.0079	0.0084	0.0090	0.0099	0.0113
900 W	0.0062	0.0064	0.0066	0.0067	0.0070	0.0072	0.0075	0.0078	0.0082	0.0087	0.0092	0.0099	0.0108	0.0122
1000 W	0.0069	0.0070	0.0072	0.0074	0.0077	0.0079	0.0082	0.0086	0.0090	0.0095	0.0101	0.0108	0.0117	0.0130

Table 9 –Volumetric Flow Rate

	Volumetric Flow Rate [ml/minute]													
	35 °C	40 °C	45 °C	50 °C	55 °C	60 °C	65 °C	70 °C	75 °C	80 °C	85 °C	90 °C	95 °C	100 °C
100 W	37.21	38.73	40.41	42.31	44.49	46.98	49.85	53.19	57.24	62.52	70.20	83.08	109.18	182.15
200 W	0.001461	0.001503	0.001551	0.001606	0.001672	0.001749	0.001839	0.001944	0.002069	0.002223	0.002430	0.002740	0.003291	0.004563
300 W	109.06	113.40	118.13	123.43	129.45	136.34	144.23	153.35	164.11	177.48	195.61	223.41	273.32	385.30
400 W	143.75	149.42	155.54	162.36	170.08	178.90	189.00	200.62	214.22	230.80	252.61	284.74	339.51	453.09
500 W	177.64	184.60	192.06	200.29	209.57	220.16	232.28	246.19	262.36	281.76	306.62	341.88	399.21	510.37
600 W	210.73	218.97	227.70	237.26	247.99	260.20	274.16	290.17	308.68	330.60	358.05	395.66	454.17	561.11
700 W	243.03	252.53	262.51	273.33	285.40	299.09	314.73	332.66	353.29	377.50	407.20	446.66	505.54	607.62
800 W	274.55	285.31	296.51	308.54	321.86	336.90	354.08	373.74	396.32	422.61	454.32	495.29	554.13	651.27
900 W	305.29	317.30	329.72	342.92	357.41	373.71	392.26	413.50	437.85	466.04	499.58	541.86	600.46	692.94
1000 W	335.27	348.52	362.15	376.50	392.11	409.56	429.37	452.03	477.98	507.90	543.12	586.58	644.91	733.14

These values were then converted to a voltage using a scaled parameter within the RSLogix 500 code that is programmed into the Allen Bradley Micrologix 1500 base processor. These values were relatively inefficient at keeping the quality of the refrigerant less than 0.7; the refrigerant would lose its thermal conductivity and cause the fan control to take time in excess of three minutes to reach its desired temperature. A new pump speed table was generated to implement a pump speed greater than that of the previous two tables. The new values are shown below in Table Z.

Table 10 – Corrected Pump Speed Values

Heat Load	% Pump Speed	Voltage Output
100 W	14	0.7
200 W	20	1
300 W	26	1.3
400 W	32	1.6
500 W	38	1.9
600 W	42	2.1
700 W	46	2.3
800 W	54	2.7
900 W	58	2.9
1000 W	64	3.2

With the new pump speeds the ICS stays within the two-phase region and the thermal energy is more efficiently transferred from the cold plate to the refrigerant. Without this changed, the controller would take more time and would be highly inefficient at removing heat from the system.

A single control strategy was implemented in order to control the fan. That general strategy can be seen below in Equation 13.

$$F[V] = F_{ss}[V] + (T_{cp}[^{\circ}\text{C}] - T[^{\circ}\text{C}]) * k[V/^{\circ}\text{C}] \quad [13]$$

where: F = Fan Output Voltage
 F_{ss} = Steady-State Fan Speed
 T_{cp} = Temperature at the Cold Plate
 T = Temperature Desired
 k = Constant Equal to 3

A separate F_{ss} for each heat load was created in order to achieve the desired response. The different steady-state values are shown below in Table 11.

Table 11 – F_{ss} for Given Heat Load

Heat Load	Steady-State Fan Speed Equation
<i>100 W</i>	$F_{ss} = -2.260\text{E-}03 * T^3 + 2.938\text{E-}01 * T^2 - 1.292\text{E+}01 * T + 1.957\text{E+}02$
<i>200 W</i>	$F_{ss} = -1.556\text{E-}03 * T^3 + 2.425\text{E-}01 * T^2 - 1.275\text{E+}01 * T + 2.278\text{E+}02$
<i>300 W</i>	$F_{ss} = -1.184\text{E-}03 * T^3 + 2.007\text{E-}01 * T^2 - 1.155\text{E+}01 * T + 2.276\text{E+}02$
<i>400 W</i>	$F_{ss} = -2.002\text{E-}03 * T^3 + 3.534\text{E-}01 * T^2 - 2.094\text{E+}01 * T + 4.190\text{E+}02$
<i>500 W</i>	$F_{ss} = -5.689\text{E-}04 * T^3 + 1.136\text{E-}01 * T^2 - 7.790\text{E+}00 * T + 1.854\text{E+}02$
<i>600 W</i>	$F_{ss} = -1.315\text{E-}03 * T^3 + 2.703\text{E-}01 * T^2 - 1.864\text{E+}01 * T + 4.341\text{E+}02$
<i>700 W</i>	$F_{ss} = -4.7298\text{E-}04 * T^3 + 1.1375\text{E-}01 * T^2 - 9.2583\text{E+}00 * T + 2.5668\text{E+}02$
<i>800 W</i>	$F_{ss} = 2.6188\text{E-}05 * T^3 + 2.2100\text{E-}02 * T^2 - 3.9510\text{E+}00 * T + 1.6430\text{E+}02$
<i>900 W</i>	$F_{ss} = -7.3317\text{E-}01 * T + 6.0186\text{E+}01$
<i>1000 W</i>	$F_{ss} = -6.4591\text{E-}01 * T + 5.4659\text{E+}01$

where: F_{ss} = Steady State Fan Speed [V]
 T = Temperature Desired [$^{\circ}\text{C}$]

Using the control strategy and F_{ss} the ICS is able to control the system within 1°C . The value k in the control strategy was manipulated in order to achieve a more aggressive change in temperature relative to the temperature difference of the cold plate and the desired temperature. Equation 13 was then multiplied by ten in the control strategy so

that the output to the fan would be a percentage as this was how the RSLogix 500 code was implemented.

SIMULINK MODELING

A Simulink model was created in order to see how close the theoretical model would be to the actual results gathered from the built system. In Figure 10, below, you can see the plant used in the Simulink model. The Simulink model, in Figure 11 is designed to show the system cooling to a desired delta temperature, the temperature difference between the desired temperature and ambient. In this model the desired temperature was set to 10°C above ambient temperature which has been normalized to 0°C. This Simulink model shows how the system responds when it is cooled from a starting delta temperature of nearly 22.5°C and cooled down to a delta temperature of 10°C over a period of roughly two and one half minutes. Figure 12 shows the response of the system as a function of time. See Appendix D for MATLAB code of Simulink plant values.

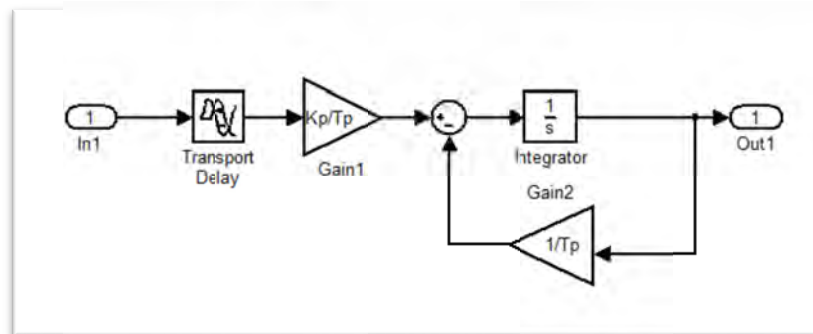


Figure 10 - Simulink Plant

The plant can be modeled as seen in Equation Y below

.....where: K_p = the steady state gain and is equal to 1
 τ_p = the time constant of the plant and is equal to 14.285
Note: μ = the delay of the system is equal to 6.2907

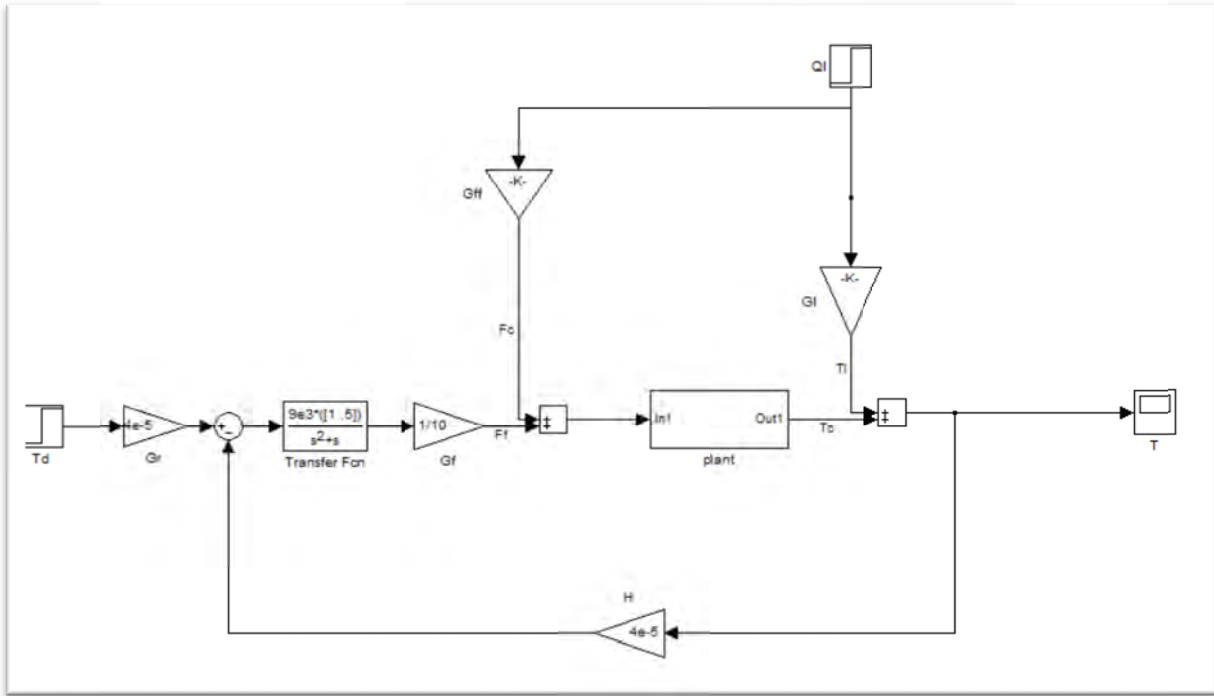


Figure 11 - Simulink PID Controller

where:

$$T_d = 10$$

$$G_r = H = 4E - 05$$

$$C(s) = 9000 \cdot \frac{s+0.5}{s^2+s} \text{ and it is denoted as Transfer Function}$$

$$G_f = 0.1$$

$$G_{ff} = 5.47E - 09$$

$$Q_l = 10$$

$$G_l = \frac{1}{500}$$

These values were measured or calculated from the physical system and then implemented in the Simulink model in order to produce results that would mimic the results of the actual system had the heat load and desired temperatures been input into the physical system. G_r and H were derived from the properties of the thermocouples. This relation involves both temperature ($^{\circ}\text{C}$) and Voltage (mV) and can be seen below in Table 12.

Table 12 - Temperature to Voltage Relationship for T-Type Thermocouple

Temperature (°C)	Voltage (mV)
20	0.79
30	1.196
40	1.612
50	2.306
60	2.468
70	2.909
80	3.358
90	3.814
100	4.279

From this table, a relationship of 1°C to $4.0\text{E-}05$ Volts was produced. G_f is the fan gain constant was it was arbitrarily chosen to be $1/10$ because one volt of the fan control input is ten percent of the fan working capacity. (1-10V control input to the fan) G_H is the relationship between pump speed and the desired heat load. This value is calculated to be $5.479 \times 10^{-9} [\text{m}^3/\text{J}]$.

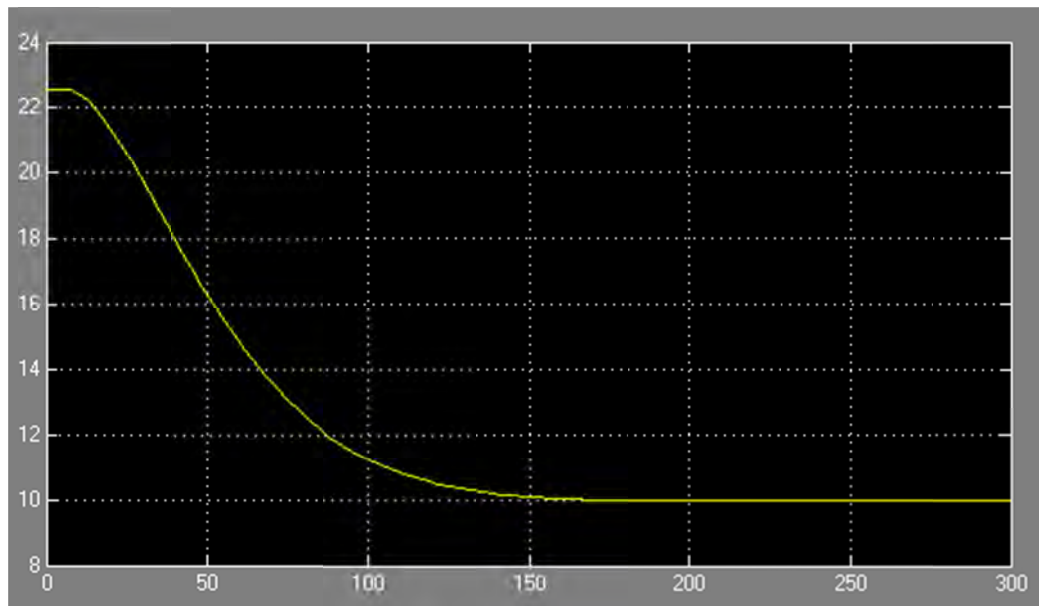


Figure 12 - Simulink Response

As can be seen above, the Simulink response is rather precise and accurate. It demonstrates the ICS, given a desired temperature of 10°C , can achieve this temperature within three minutes.

ELECTRICAL CONNECTIONS

The ICS will be getting all of its electrical power from a standard wall outlet: 120VAC. A power entry module is plugged directly into the wall outlet and this is there to isolate the system from the main power supply for safety reasons. It also helps to be able to cut off power to the ICS when needed. This delivers the 120VAC straight from the wall without modifying it. A 24VDC power supply is connected to the power entry module and it outputs 24V for various DC components in the ICS. [13]

The PC and monitor also get their 120VAC power from the power entry module. The Data Acquisition (DAQ) hardware and the DIN-A-MITE (which controls the resistive heaters/heat source) also get their power (120VAC) from the power entry module.

The 24VDC power supply supplies voltage to the pump, the fan, the flow meter, and the pressure sensors. The DIN-A-MITE supplies current to the heaters which give off heat corresponding to the signal from the user input. The DIN-A-MITE converts this input signal to the appropriate signal needed by the heaters to provide the correct heat output.

The input signal for the pump is obtained from the DAQ/control system. This signal is calculated based on the heat input and the quality of refrigerant that is desired.

The signal input to the fan is also obtained from the DAQ/control system. Based on the temperature input of the heat source given by the sensor, the control system preforms the algorithm to output the corresponding signal to the fan which removes the appropriate amount of heat from the system. Other sensor inputs such as pressure from all nodes [11], flow rate of the refrigerant and temperatures from all nodes go into the DAQ as well.

DATA ACQUISITION AND SIGNAL PROCESSING

Data acquisition is the process of gathering physical readings from sensors and converting it into a usable analog signal then processing the signal. Once the usable analog signal has been generated, the data acquisition system filters the signals so that it can be converted to a digital signal. The output desired from the control system is then sent back to a controlled device via an analog output signal from the data acquisition system.

For the ICS, the sensors include: thermocouples for temperature measurement, pressure transducers for pressure measurement, and a flow meter to measure the flow rate of the moving refrigerant. These sensors will output an electrical signal based on that specific transducer's properties. For the ICS the thermocouples will output a voltage, the pressure transducers will output a current between 4 and 20mA, and the flow meter will output a voltage signal based on the flow rate of the system. Figure 13 is a diagram of the system showing where the different sensors will be placed.

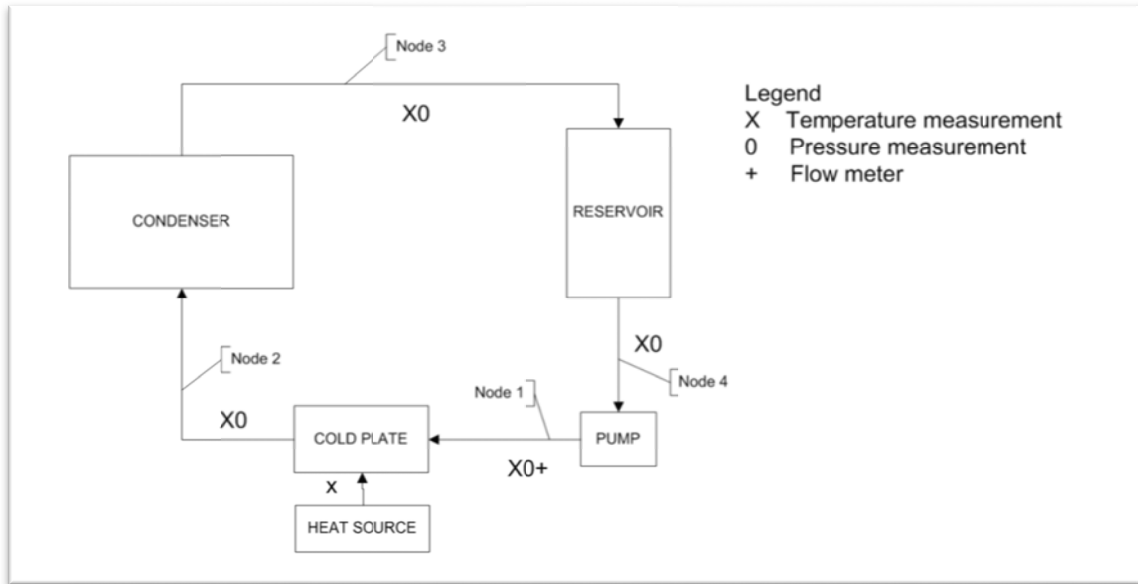


Figure 13 - Schematic of the ICS with Sensor Placement

Once the sensor data has been acquired the DAQ will then condition the electrical signals to filter out the noise and erroneous data. This will be done by the data acquisition hardware. These filtered signals will then be converted to a digital signal using an analog-to-digital converter in the DAQ. Once the controller has determined the desired fan speed for the signal, the controller will output an electrical signal to the DAQ. The DAQ then sends an analog voltage to the fan.

TOUCHSCREEN AND USER INTERFACE

The touchscreen selected for the ICS is the HP Compaq L2105tm monitor. The 21.5 inch optical touchscreen monitor was lower in price after more investigation using the Parker company discounts. The monitor will be attached to a personal computer using a USB port and a VGA cable connection. The monitor's included stand will be removed

and instead the monitor will be secured directly to the aluminum extrusion frame of the ICS using a quick-release VESA 100mm bracket.

The user will be asked to choose a device to be cooled or create a custom scenario by pressing the desired option on the touchscreen. If a predefined electrical component is selected, pre-programmed input values will be used for the control system. If a custom scenario is selected, the user will be asked to enter in a heat load and desired temperature of the device being cooled. To enter in the heat load and desired temperature, the user will input these values by touching the corresponding options on the touchscreen.

After the inputs have been entered, the system will begin working to meet the desired temperature. While the control system is in operation, the pressure and temperature at each node will be displayed. The flow rate of the refrigerant, temperature of the heat source, and ambient temperature will also be displayed.

Section II:

Building Process

PROCUREMENT

To complete the senior design conceptual design, a detailed list of components, material, tools, and supplies were composed and ordered through Parker Hannifin. This bill of materials was continuously updated and adjusted during changes in production of the ICS units and quotes/consultations with suppliers. The bill of materials for the display unit is documented in Appendix E. This list includes the following:

- Description
- Manufacturer
- Manufacturer Number
- Supplier
- Supplier Number
- Use in Interactive Cooling System Unit
- Unit Price
- Quantity
- Total Price
- Quote Number
- Quote Date
- Order Date
- Parker Purchase Order (PO) Number
- Received Date
- Calculated Lead Time

Once the supplies arrived, the ICS began to take shape. The construction of the unit is briefly described in the following sections: display cabinet construction, two-phase cooling construction, electronics assembly, programming, and finishing touches. Each section is further divided in to subsections and is explained below.

DISPLAY CABINET CONSTRUCTION

FIBERGLASS SHELL MOLD MAKING

To develop a fiberglass cabinet with the custom design shown in Figure 14, a fiberglass mold was created. Hoosier Patterns Inc. is a local company that specializes in mold making for industrial applications. After an on-site meeting and email correspondence with Keith Gerber and Dave Rittmeyer (the president and CAD supervisor of Hoosier Patterns, respectively), it was agreed to CNC machine high density, fine foam to construct the mold for the fiberglass shell. Due to the size of the ICS in relation to the

maximum table size of Hoosier Pattern's CNC machine, the mold was created by machining nine different pieces that were then glued together to make the final mold. See Hoosier Pattern's machining and mold making process in Figures 15 to 22.



Figure 14 - Cabinet 3D Rendering

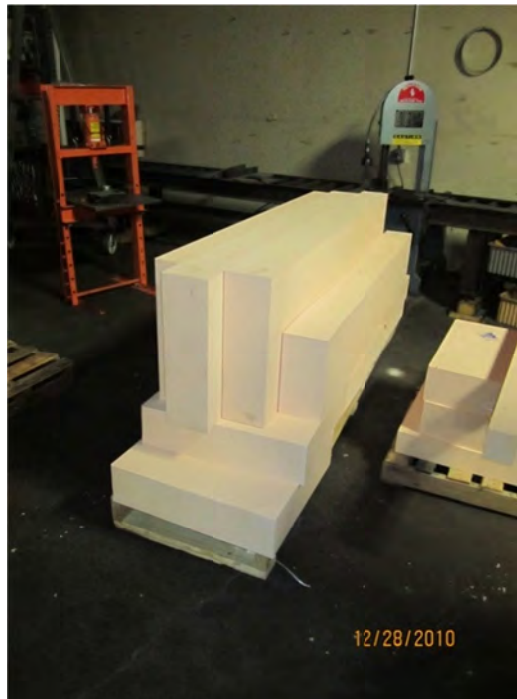


Figure 15 - Large High Density Foam Purchased For Fiberglass Mold



Figure 16 - Small Pieces of High Density Foam for Fiberglass Mold



Figure 17 - Machining of Left Middle Section of the Fiberglass Mold



Figure 18 - Side View of CNC Machining



Figure 19 - Top Plate Machining of Fiberglass Mold



Figure 20 - Top Plate of Fiberglass Mold in CNC Machine



Figure 21 - Bottom View of Fiberglass Mold in Assembly Process



Figure 22 - Alternative View of Fiberglass Mold in the Assembly Process

ALUMINUM FRAME CONSTRUCTION

A skeleton frame was designed to house and support the fiberglass skin as well as the touch screen, computer, DAQ, and two-phase cooling cycle. To accommodate this, Parker's Electromagnetic Division's Industrial Profile System (IPS) was used to construct the entire display unit's frame. The design of the aluminum frame utilized 40mm, standard weight, IPS with 28mm to support two-phase cooling accumulator, sight glass, and cold plate. To secure IPS to each other, various methods of buttress connectors, angle brackets, and tapped holes for socket head cap screws were used. See the base and frame pictures in Figures 23 to 26 for frame details. The frame was divided into a base, shelves, and structure members to make the final assembly rendered in Figure 26.

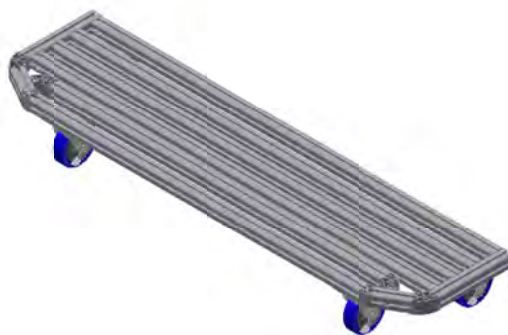


Figure 23 - Assembled Aluminum Frame Base of ISC

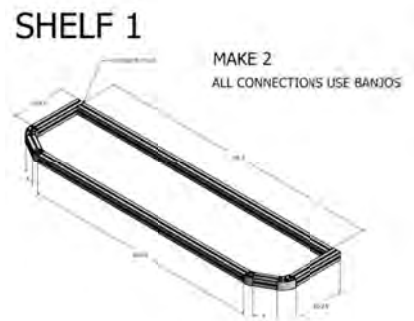


Figure 24 - Shelf 1 Assembly and Dimensions for Aluminum Frame of ICS

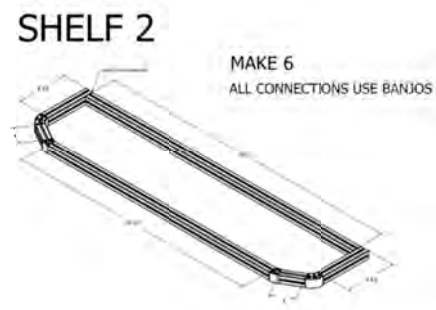


Figure 25 - Shelf 2 Assembly and Dimensions for Aluminum Frame of ICS



Figure 26 - Assembled Frame of ICS

FIBERGLASS SHELL CONSTRUCTION

Once the machined mold arrives at Hy-Tec Fiberglass Inc. facility, the mold was gel-coated to insure that cured fiberglass can be removed and the mold can be reused in the future. Due to the size of the mold, blowholes are drilled in key locations of the mold to assist the manufacturer when it the ICS fiberglass is removed. The technic used was to blow compressed air inside the bottom of the mold to release the large flat surface that is prone to sticking. Gel coating is shown in Figure_.



Figure 27 - Gel Coating of Fiberglass Mold

Once the mold is gel coated, it is then sanded and finished to a clean surface. This helps the final outside finish of the fiberglass to ensure it is smooth as possible. Finishing is shown in Figure 28. The red marks are the covered blowholes.



Figure 28 - Mold Finishing

The next step in the fiberglass process was to begin to lay key panels of thick fiberglass panels cut to mimic the contours of the mold. See Figure 29 for fiberglass laying.



Figure 29 - Fiberglass Panel

Then a thick layer of resin is painted over the top of the fiberglass panel in generous quantities to completely saturate the panel. More and more fiberglass panels and resin are used to build a total of 1/8" thick fiberglass skin once it is cured. See Figure 30 for resin application.



Figure 30 - Resin Application

Once the aluminum frame is briefly dry-fitted to verify the dimensions, the fiberglass manufacturers continue to spray a back 'lip' onto the inside of the mold after attaching a barrier to make the back of the unit more easily accessible with the creation of reinforced fiberglass doors. Once the whole fiberglass skin, still in the mold, cures, it is then painted on the inside of the fiberglass to make the final display cabinet easier to assembly and maintenance on the inside. The aluminum frame is then inserted from the bottom of the mold and placed appropriately in the mold. Selected members of the aluminum frame are then 'fiber-glassed' into place to make the final bond between the frame and the fiberglass shell. The frame and fiberglass assembly is then hoisted out of the mold by an overhead lift and blown out of the mold through the blowholes to overcome the suction effect: see Figure 31.

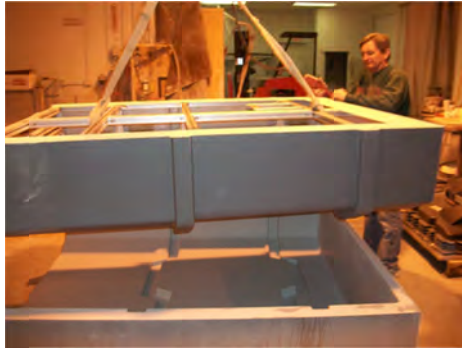


Figure 31 - ICS Removed from Mold

Doors are made from reinforced fiberglass and epoxied in place to the lip of the back of the fiberglass shell with the aid of piano hinges. The fiberglass cabinet is then one step closer to completion.

CUSTOMIZED CUT-OUTS

To accommodate and showcase the two-phase cooling technology, the unit undergoes selective cutting. Using a provided template of the size and placement of the fiberglass, the following components required cut outs:

- Power-Entry Module
- Fan Air Intake Grill
- Touch Screen
- USB Ports
- Accumulator
- Pump Manifold
- Condenser
- Level Indicator Sight Glass
- Cold Plate Assembly

See the following Figures 32 and 33 for views of the final fiberglass cut-out size and placement of the primed cabinet.



Figure 32 - Rear View of Primed ICS Cabinet with Fan Air-Intake Grill



Figure 33 - Front View of Primed ICS Cabinet with Essential Two-Phase Cooling Cycle Cut-Outs

PAINTING AND FINISHING

The unit is first primed and allowed to cure and then sanded to a smooth finish before painting. The first coat is the color for the pin-stripping bands above the top 3D border and below the bottom 3D border). After it is allowed an ample amount of cure time, it is buffed smooth. The next stage of painting is the top and middle section of the unit. The unit is masked off to cover the exact pinstripe and the middle section. These sections are also allowed ample amount of time to cure and then buffed smooth. The next coat of color is the middle section. The finished top and bottom sections are then covered, before the middle is painted. Curing time and buffing follows. The last color is the 3D borders. The entire unit minus the area of the borders is masked off. The paint cures and is buffed appropriately. After all the sections are painted, cured, and buffed, the masking comes off including the strip covering up the pinstripe. The unit is then clear coated and buffed twice to unveil a car-body finish. See Figures 34 to 38 for photos taken during the painting process of the IPFW donation unit. Same process was repeated for the Parker ICS unit.



Figure 34 - Pinstripe Painted



Figure 35 - Top and Bottom Painted



Figure 36 - Mid-Section Painted



Figure 37 - 3D Borders Painted



Figure 38 - Rear View of Finished Fiberglass Cabinet with Clear Coats

CASTER ADJUSTMENTS

Before the unit is set up-right after the unit arrives from Hy-Tec Fiberglass, the casters are removed and cleaned thoroughly. Due to the dirty, dusty environment of the fiberglass manufacturing, the display cabinet is covered in fiberglass dust that needed to be removed. After the casters were removed from the base of the unit, the four bolts holding them in place were applied a generous amount of Lock-Tite thread glue and screwed back into place. This ensures that rigorous travel and vibrations from moving the unit on uneven surfaces, does not cause the caster bolts to loosen and eventually fall out leading to a catastrophic collapse of the unit.

The final IPFW cabinet at Parker's Engineering Lab is showcased in Figures 39 to 41.

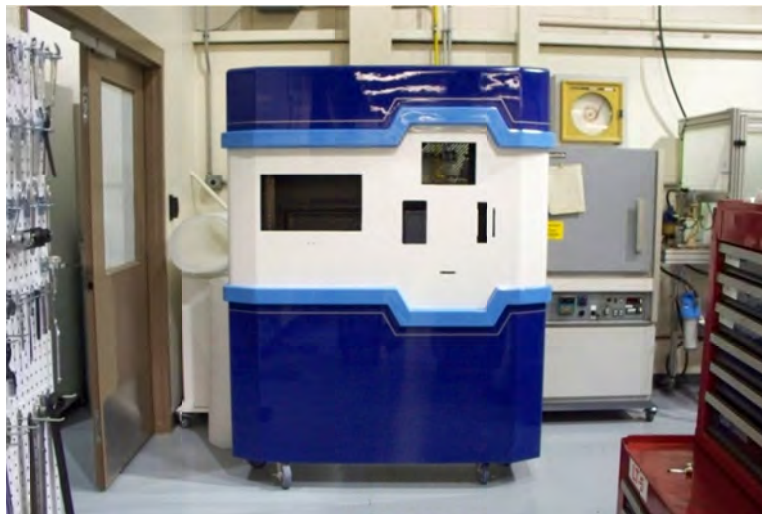


Figure 39 - Finished Cabinet Delivered to Parker's Engineering Lab (IPFW Unit)



Figure 40 - Finished Rear View of Finished Cabinet Delivered to Parker's Engineering Lab (IPFW Unit)



Figure 41 - Side View of ICS at Parker's Engineering Lab

TWO-PHASE COOLING CONSTRUCTION

TESTING RIG

In order assist the assigned brazier of the ICS, a testing rig was built in order to house the two-phase cooling system pieces and parts during the assembly/brazing process. See Figure 42 for the isometric view of the testing rig.

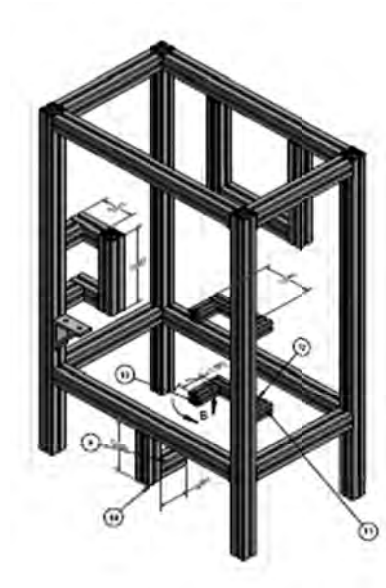


Figure 42 – Isometric View of Testing Rig



Figure 43 – Testing Rig with Installed Two-Phase Cooling Cycle

BRAZING

Brazing was performed by the in-house Parker professional brazier, Chris Gorman. He first took the specified drawings of each copper tubing bend (see Appendix F for all copper tubing segments made) and their 'xyz' corner bend locations, programmed them into his copper tubing bending equipment and cut them to size. He then cleaned and began assembling each sub assembly according to the schematics shown in Appendix G. Each sub assembly was individually leak tested with helium. The final assembly included attaching the pump to the pump manifold and the encasing the cold plate with the custom designed and machined cold plate housing. See Appendix A for the pump manifold and cold plate housing detailed dimensions.

COLD PLATE HOUSING ASSEMBLY

The most complex and important assembly of the two-phase cooling cycle is the cold plate and cold plate housing assembly. The first step is to clean the 7" x 3.5" x 1" tempered borosilicate glass with industrial cleaner to remove all fingerprints and residue before assembly; see Figure 44 for cleaning. Second, the cold plate was thoroughly and meticulously cleaned with scotch bright to remove all fingerprints and unwanted discoloration of the copper cold plate. See Chris Gerardot cleaning the cold plate in Figure 45. Third step is to apply O-ring grease to the entire cold plate O-ring to insure a tight face seal shown in Figure 46. The next step is to insert the O-ring and then place the cold plate into the bottom of the cold plate housing plate as shown in Figures 47 and 48, respectively. Place the cleaned tempered glass on top of the cold plate with a cloth to ensure there are no fingerprints as seen in Figure 49. Place the top cover of the cold plate housing assembly over the glass and cold plate without scraping the glass as demonstrated in Figure 50. Gently flip the whole assembly over (Figure 51) and begin inserting ¼-20 x 1 inch socket head cap screws (SHCS) into each threaded hole in the cold plate housing cover through the clearance holes in the bottom housing plate. Use 70ft-lbs to torque each screw down as seen in Figure 52. The completed cold plate housing is modeled by James Stoller in Figure 53. The heaters were applied with thermal paste and one thermocouple was placed in the middle of the second heater, closest to the exit of the cold plate. The assembly is shown in Figure 54.



Figure 44 - Cleaning of Borosilicate Glass



Figure 45 - Overall Cleaning of the Cold Plate



Figure 46 - Rubbing O-Ring Grease over Entire O-Ring



Figure 47 - Place O-Ring in Cold Plate

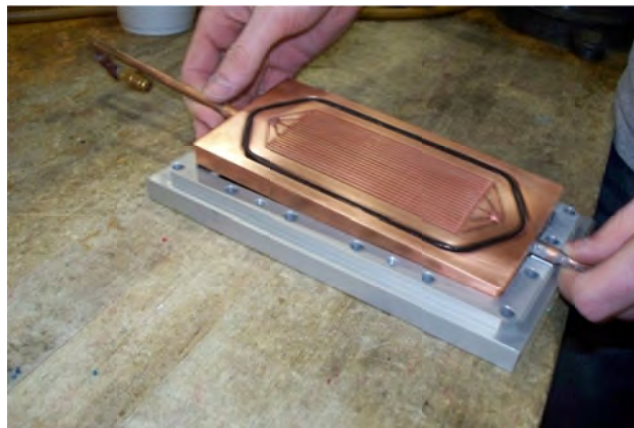


Figure 48 - Place Cold Plate in Cold Plate Housing Bottom



Figure 49 - Place Clean Glass over Top of Cold Plate

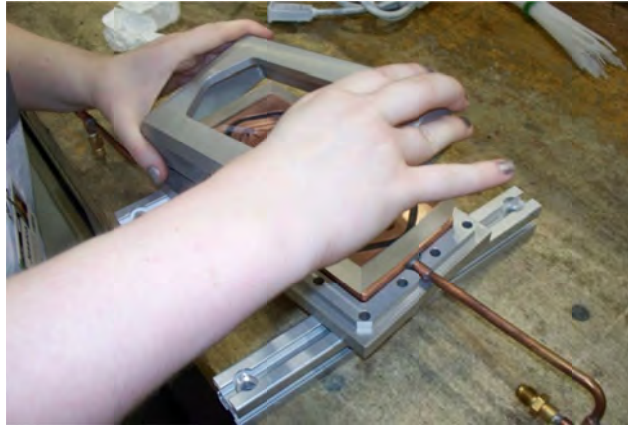


Figure 50 - Place Cold Plate Housing Cover over the Top of Glass and Cold Plate

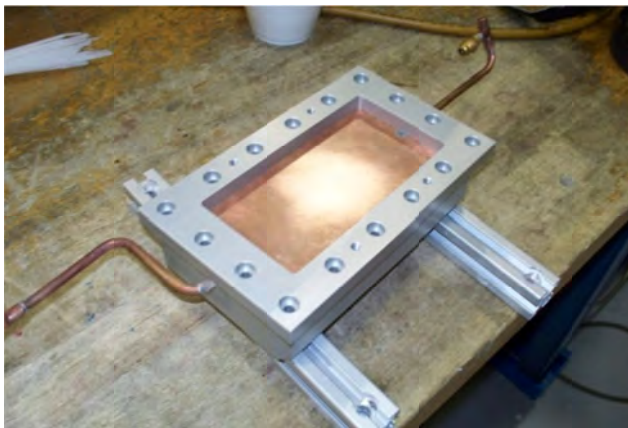


Figure 51 - Cold Plate Assembly Flipped Upside Down



Figure 52 - Cold Plate Housing Assembly with Continued Torque Applied



Figure 53 - James Stoller and His New Baby

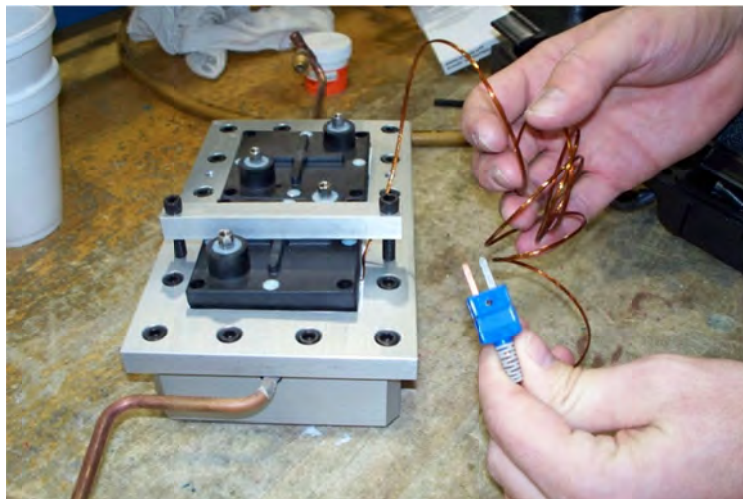


Figure 54 - Assembled Cold Plate Housing with Heaters and Thermocouple

CYCLE TRANSFER

Once the entire cycle is assembled, brazed, and leak checked, the entire system is transferred from the testing rig to the cabinet. This requires multiple hands and strength. Figure 55 shows the difficulty of rotating the whole two-phase cooling cycle out of the testing rig and rotating it under the shelves in the cabinet before the IPS was attached to the cold plate and the accumulator can support the weight of the system without bending the copper tubing. The pump manifold, accumulator, and cold plate were dry-fitted prior to the cycle transfer to verify the components would indeed fit through the fiberglass cut-outs.

If tolerances did not allow each component to fit through, the openings were filed down until they matched and allowed the components to push through without scraping.

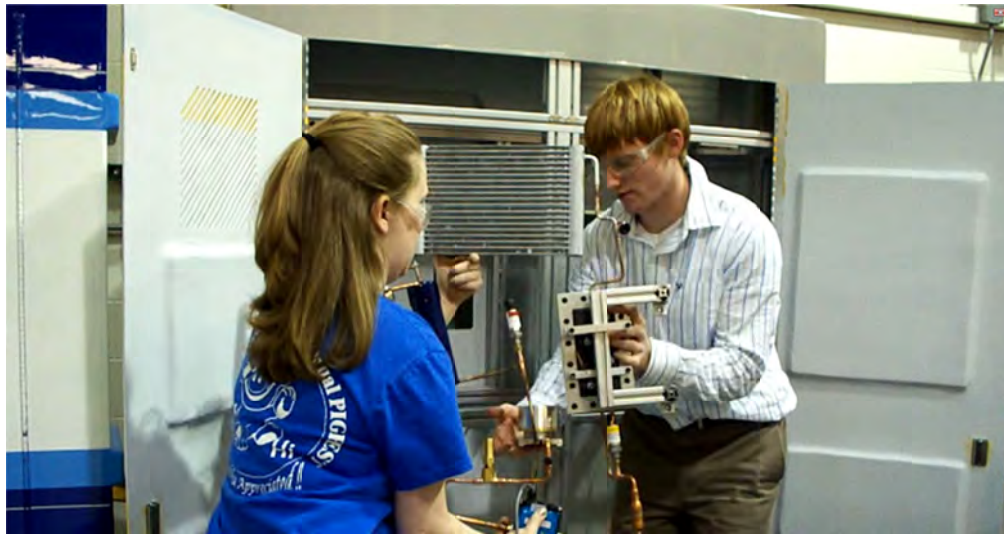


Figure 55 - Jessica Hunnicutt and Christopher Gerardot Placing Two-Phase Cooling Cycle into Parker ICS Cabinet from Testing Rig (not shown)

SHROUD CONSTRUCTION

The fan shroud was constructed from mild steel sheets using the pattern made in advance. The templates were plot in 1:1 scale and cut out appropriately. Using traditional duct work bending methods, the edges made on the shroud were bent and glued into place using duct caulking. See Figures 56 thru 58 for pictures showing duct construction.



Figure 56 - Metal Bending



Figure 57 - Shroud Construction

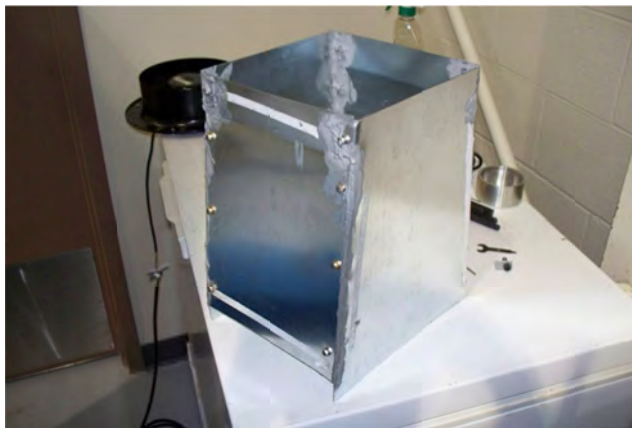


Figure 58 - Final Shroud

FAN AND SHROUD INSTALLATION

Due to the tight proximity of the condenser, shroud, and fan final placements, they were assembled individually in the cabinet. The condenser is verified of placement in relation to the condenser cut-out on the fiberglass. The shroud is then maneuvered into place beneath an IPS member and caulked into place on the top and bottom lips. The flanges are then inserted and twisted into place with a bead of duct caulk attaching it to the shroud and to the manifold of the condenser. The IPS holding the fan is then inserted from the bottom and secured to the aluminum frame of the cabinet. The fan is then gently, but forcefully, placed inside the shroud opening. The fan is then twisted to align 3 holes along the tracks of the IPS and secured with IPS drop-in T-nuts. The fan cowl and shroud is then foamed to minimize/remove all air leaks that could cause the fan to blow air other than to the condenser.

ELECTRONICS ASSEMBLY

The touchscreen for the interior unit is a remounted HP touchscreen monitor. The monitor is first laid down with the touch screen facing downward. A Philips screw driver was used to remove the monitor stand, Figure 59, included in the shipment of the monitor. A Quick-Release mount was purchased and the included instructions of the bracket were followed accordingly. The attachment of the back plate is shown in Figure 60. Using drop-ins for 40mm IPS aluminum extrusion, the front plate of the Quick-Release mount is placed on two pieces of the IPS, Figure 61. Once secured, the placement is tested (Figure 62) and placed in the cabinet. The touchscreen is then attached to the IPS by sliding the Quick-Release Bracket together as demonstrated in Figure 63. Wires required for the touchscreen include the monitor power supply, USB cable for touchscreen capabilities, speaker wire, and VGA cable. These are organized in a raceway track and connected to the appropriate terminals on the back of the computer.



Figure 59 - Remove Monitor Stand from Monitor



Figure 60 - Screw Back Plate of Quick Release Mount to the Monitor Recommended Screws

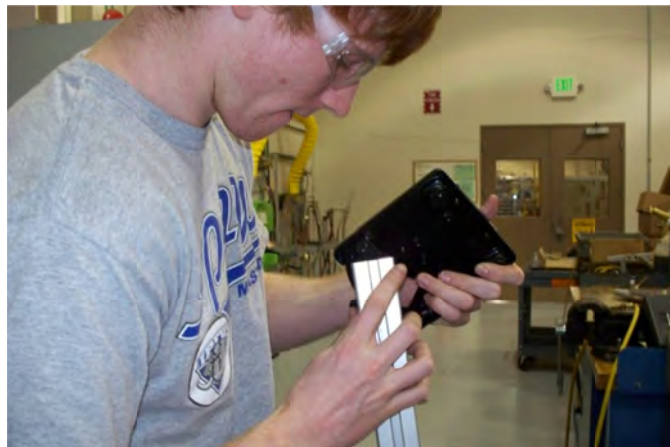


Figure 61 - Attach the Quick Release Mount Front Plate to IPS



Figure 62 - Check the Alignment and Screw down IPS to Designated IPS Pieces that are Pre-Installed in Cabinet



Figure 63 - Temporarily Engaging the Quick-Release Mounting

COMPUTER INSTALLATION

To attach the computer to the inside of the fiberglass unit, ratcheting straps were utilized in securing the front and back of the computer as shown in Figure 64. The excess nylon straps were cut off approximately one inch from their exit of the ratchets. The wires connected to the computer include: the computer power cord, the VGA cable coming from the touchscreen, the audio cable coming from the touchscreen, and the USB cable coming from the touchscreen, the USB extension cables coming from their holders mounted beneath the touchscreen and the serial cord connected to the DAQ system. The computer is oriented to place the wires entering/exiting the computer into the installed raceway track to maintain an organized appearance and function.



Figure 64 - Computer Orientation and Ratcheting Straps

ELECTRICAL WIRING

In wiring the ICS, all electrical wiring codes were followed. This means that blue wires were used for DC signals, black wires for hot 120 VAC signals, white for neutral and green for ground. The gauges of the wires were taken into account when installing in order to avoid overheating of the wires. The whole ICS unit gets its electrical power supply from a standard wall outlet: 120VAC. A power entry module is utilized in the unit for safety reasons and also to make it easier to turn the unit power on and off. The power entry module is a device with a switch in it so that even if the ICS is plugged into the wall, as long as the switch isn't pressed on the ON side, there would be no power to the unit. [12] A picture of the power entry module is provided in Figure 65. A power strip with several outlets for 120 VAC is then connected to the power entry module inside the unit so that it can provide power for the various components that need 120 VAC such as the CPU, the touch screen monitor, the Allen Bradley DAQ base unit/processor, the DIN-A-MITE, the STATUS SEM, and the 24 VDC power supply.



Figure 65 - Power Entry Module

All of the electronic components were mounted on DIN rails which were then secured to the internal aluminum skeleton of the ICS. The DIN rails provided great support and flexibility. They were convenient, because all of the components were shaped in a way that they could be mounted on DIN rails and so they could be slid from side to side in order to make room or create adequate spacing between components. DIN rails also provide grounding capabilities. Terminal blocks or DIN-nectors also proved very helpful in connecting several wires together without all the connections being not organized.

The Allen Bradley DAQ consists of a base module and if needed, several I/O modules connected to the base processor which must then be terminated with an end cap. The base unit used is the Micrologix 1500 LRP series and it contains the processor, supplies 24 VDC to the other attached modules, has LED indicators, and contains some I/O ports. The expansion I/O modules used include a 4 channel output module to send control signals to the fan, pump, and heater, an 8 channel analog input module to get readings

from the pressure sensors, a 4 channel analog input module to get readings from the flow meter and finally, a 6 channel thermocouple input module to get pressure readings. At the end of the row, a terminal end cap is attached to close the circuit. A picture of the DAQ assembly is provided below in Figure 66.



Figure 66 -DAQ Assembly

The Allen Bradley base unit was given inputs for L1 (hot), L2 (neutral), and ground from the 10 VAC power strip. Next, hot, neutral and ground wires were also connected to the 24 VDC power supply and at the output of the power supply, blue wires were connected for both +24 V and common. Hot, neutral, and ground wires were also connected to the DIN-A-MITE which is the device that sends the current signal to the resistive heater blocks placed underneath the cold plate. A 30A fuse was placed in series with the hot wire connection to the DIN-A-MITE in order to protect the circuit. Hot and neutral wires were also connected to the STATUS SEM which is the device that was used to convert voltage to current that will be passed through the resistive heaters.

The DAQ outputs a 0 to 10 VDC signal for the heaters and sends this signal to the STATUS SEM. This device has many configurations of use depending on how the internal DIP switches are set. Since the input was 0 to 10V and an output of 4 to 20mA was desired, the internal DIP switches 1, 2 and 3 were set to 0010, 00, and 0001, respectively. The output of the STATUS SEM (a 4 to 20 mA signal) is then sent to the DIN-A-MITE and then the DIN-A-MITE sends it to the heaters.

There are 2 heaters used and they are connected in series with each other. A black wire comes straight from the DIN-A-MITE to one end of one of the heaters, the other end of the first heater is connected to one end of the second heater with another black wire and finally, a white wire goes from the other end of the second heater back to the DIN-A-MITE to complete the circuit.

The DAQ also outputs a 0 to 10 VDC control signal to the fan. The fan gets +24 VDC from the positive side of the 24 VDC power supply and the common lead of the fan is connected to the negative side of the DC power supply. The positive terminal of the output channel for the fan is connected to the control lead of the fan while the negative terminal of the output channel for the fan is connected to common. The fan is capable of 550 cfm at full speed 10 V and this corresponds linearly to the 0 to 10V control input. The fan is manufactured by EBM Pabst and was discussed in Section 1: Detailed Conceptual Design.

The DAQ outputs a 0 to 5 VDC control signal to the pump. The pump is a silencer smart series pump manufactured by Diener. The pump gets +24 VDC from the positive side of the 24 VDC power supply and the common lead of the pump is connected to the negative side of the DC power supply. The positive terminal of the output channel for the pump is connected to the control lead of the pump while the negative terminal of the output channel for the pump is connected to common. The pump is capable of 1000 ml/min at full speed 5 V and this corresponds linearly to the 0 to 5V control input.

The pressure transducers used were the P499 series electronic pressure transducers manufactured by Johnson Controls. [4] A pressure transducer was placed at each of the 4 nodes in the thermal cycle. They output 4 to 20 mA current proportional to a pressure of 0 to 500 psi. These pressure transducers have 3 leads (red-supply, white-output, black-common) but since their output is current, they are only used in a 2-wire configuration (red and black). The red wires of all the pressure transducers were connected to +24 VDC and the black wires were each connected to the positive terminal of channels 1 through 4 on the 8 channel analog input module. Each negative terminal of channels 1 through 4 were connected to analog common on the input module (which are all internally connected) and then the negative side of the 24 VDC power supply was connected to one of the analog commons. The current produced by the pressure transducers will be in the range of 4 to 20 mA and this current reading will be transferred to the base processor and converted to a pressure reading based on the configuration of the module. A picture of the pressure transducers used is shown below in Figure 67.



Figure 67- Pressure Transducer

The flow meter used was a Proteus 8000 series liquid flow meter and it outputs a 0 to 5VDC signal to the DAQ input module which then converts it to a flow measurement in gallons per minute (gpm). [8] [9] The flow meter was rated for 0.05 to 0.3 gpm and since this range was tight, the units were converted to mL/min and that was displayed on the screen instead. A 24 VDC signal was connected to the flow meter as well as a common signal. The output signal of the flow meter was then connected to the positive terminal of the input module channel and the negative terminal was connected to analog common on the DAQ. Analog common on the DAQ was then connected to the negative terminal of the 24 VDC power supply.

The thermocouples used were T-type thermocouples made by Omega. [7] They came in 36" lengths with one end of the dissimilar metals soldered together and the other end in a plastic terminator. Since some of the thermocouples were going to be placed more than 36" away from the thermocouple input module, their lengths had to be extended. First, a rough estimate of how long each of the six thermocouples had to be was made and then extra thermocouple wire had to be obtained, cut to length and then terminated with a corresponding plastic terminal so they could be attached to the purchased thermocouples. The thermocouples were hooked up with the positive sides to the positive terminal of each channel in the DAQ and the negative sides to the negative terminal of each channel in the DAQ. There were four thermocouples attached to each node in the thermal cycle by first placing thermal grease on both the copper pipe and thermocouple tip, placing the thermocouple on the pipe and then taping them tightly together with insulation tape and then securing the whole thing with electrical tape. There was a separate thermocouple to measure ambient temperature. For this, a hole was drilled in the side of the fiberglass shell about 3 feet from the ground and then the thermocouple was pushed through this hole and secured in place. The thermocouple at the base of the cold plate was placed in between the cold plate, which had been rubbed

with thermal grease, and the two resistive heaters forming a sandwich. Figure 68, below, shows a thermocouple that was used in the ICS.

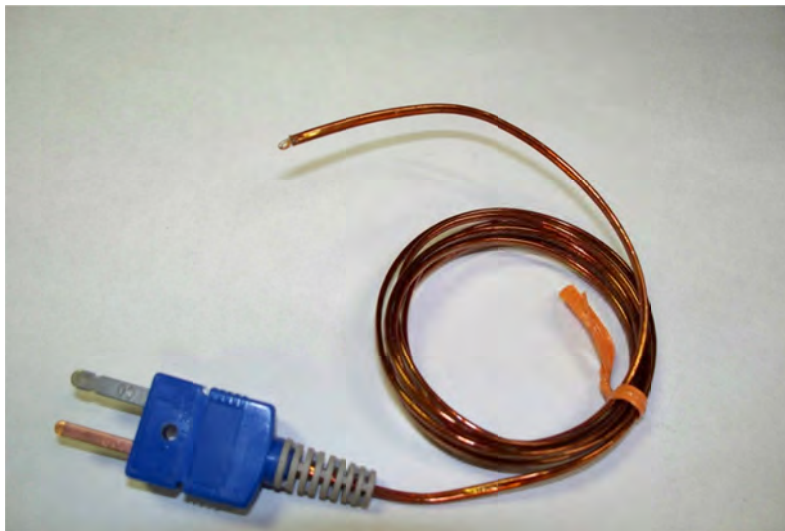


Figure 68- A thermocouple

An electrical connection diagram of the ICS is provided in Appendix H.

COMMUNICATION BETWEEN PROCESSOR AND TOUCHSCREEN

First, the PC was set up so that it doesn't go to sleep mode or log off due to inactivity. This keeps the screen always active.

The software that was used to program the user interface is called InteractX 3.0. This software is used in manufacturing plants and factories for Human Machine Interface (HMI) and controls. Two different applications were set up during the course of this project: Application A called "Testing3_21.gms", to provide an interface to carry out the testing of the ICS and Application B called "ICS.gms", to be used in the finished product where the user can select their inputs of heat load and desired temperature and the ICS automatically regulates itself.

InteractX makes use of devices called tags. These can be likened to variable names in regular programming like C programming. These tags contain values like integers, floats, strings and even binary information. InteractX also has numeric displays to display numerical values which could be values stored in tags. There are also action buttons available; mostly these enable the user to move on to another panel (screen). Then there are discrete buttons used primarily for turning certain bits on and off. There are a wide range of useful 'tools' like this in InteractX which are located in the Tool Bin.

InteractX is designed to work hand in hand with the DAQ systems. The applications created were linked to the Allen Bradley equipment used by creating and setting up the channel and device and connecting the Allen Bradley base unit to the PC using the cable provided. InteractX can also display sensor values if these values are set up so that they are stored in these tags.

For the InteractX application A, the inputs were heat load, fan speed, and pump speed. The values to be displayed were the temperatures, pressures, flow rate of refrigerant and quality of refrigerant at the exit of the cold plate. Numeric Display tools were used to display all of these. In addition, buttons were created to increment or decrement the inputs so that certain test points could be created. As soon as an input is incremented, the new value is displayed on the screen and also written to the tag. This information is sent to the DAQ and the processor sends the right current/voltage to the output module of the DAQ and the equipment connected to the corresponding channel on the output module acts accordingly. [10] A discrete button was also added on the screen to start and stop the whole system in toggle mode. After it is pressed, then any changes to the input values will take effect. After testing is completed, in order to turn the heat and fan off, one can either decrement the inputs to zero and/or just press the start/stop discrete button and it turns back to green - waiting for the system to be started again.

The InteractX application B which was created for the final product was more complicated and more in-depth; for one, it was comprised of many screens with some depending on the previous one and also with the ability to go back to previous screens. The user manual, which is provided in Appendix I, gives a detailed description on how to navigate these screens. The first screen allows the user to start the system for the developed run-time environment. The start/stop discrete button, described earlier, is present here. After this button is pressed, then an action button is used to advance to the next screen. There is also an exit button on this screen to exit the run-time environment, but this only shows up when the system has been stopped by pressing the start/stop button.

The ICS provides options to the users to either simulate the cooling of 3 devices called Device 1, Device 2, and Device 3, respectively, or to create their own custom device which they intend to cool. Device 1 has a heat load of 200 W and a set desired temperature of 42°C; Device 2 has a heat load of 500 W and a set desired temperature of 60°C; Device 3 has a heat load of 800 W and a set desired temperature of 65°C. This selection of pre-defined heat loads and desired temperatures is achieved using discrete buttons. When a Continue action button is pressed, the screen shows a page where the

user can make different selections. On this page, the user can start the data logging process, press a button to view advanced calculations such as enthalpy and entropy at each node, press another button to view a temperature vs. time graph of the temperature at the cold plate, press a button to view the temperature and pressure at each node, and so on.

The data logging was set up so that data is saved every second from the time the data logging discrete button is pressed to the time it is pressed a second time to stop the data logging. The data is stored in a Microsoft Access file on the desktop called "Data.mdb". When this file is opened, the data is found in a table called "Mytable". This data can be exported to Microsoft Excel and then manipulated from there.

If the custom setting is chosen, the user selects a heat load from 100 W to 1000 W in 100 W increments. This is achieved using value buttons. A numeric display button also shows what input was selected by the user. At the next screen, the user selects the desired temperature by a similar process. Here the screen is programmed to only display options of desired temperature that the device can be cooled to (and allowed maximum temperatures) based on the heat load input that was chosen. After pressing the Continue button, the screen shows the user the custom inputs that were selected so the user can review before proceeding. If the user is not satisfied, they can use the Back buttons to make changes

To exit the run-time environment, the user just has to click the Home action button which takes them to the welcome page where the whole adventure began. The user must click the Stop button before the Exit button appears. This feature is one that is available in InteractX where certain parts of the screen do not appear until a certain condition is met. After pressing Exit, that is the end of the interactive session.

FINISHING TOUCHES

LOGO PLACEMENT

The logo for Parker was ordered as a black vinyl decal. A 0.25" thick piece of acrylic was machined and routed to place through the 1/8" thick fiberglass and glued into place. A scrap piece of IPS 40mm extrusion was mounted to the back side of another piece of acrylic in which a white LED rope light was secured in a serpentine pattern for even light distribution. Once the acrylic glued to the fiberglass cured, the vinyl cut-out

decal of the Parker logo was gently smoothed on with the aid of a plastic scrapper to remove air bubbles. See Figure 69 for a picture of the final back-lite logo.



Figure 69 - Parker Backlit Logo

GRAPHIC ART PLACEMENT

The final graphic design finalized with the aid of Richard Carissimi, was sized and ordered on matte vinyl. Once received, the fiberglass was gently marked with pencil for centerlines on the face and on the decal transfer paper in order to assure correct vertical and horizontal placement. A level was used to verify that the vinyl decal was not tilted in either direction. See the vinyl art also shown in Figure 69.

UNDER CABINET LIGHTING

The cabinet was accented with under-lighting. This was done with the use of plastic P-clips mounted to the underneath side of the IPS base and centered around the entire perimeter of the unit. The power cord was then zip-tied and plugged into the power strip of the unit. See Figure 70 for underbody light reflection shown.



Figure 70 - Parker ICS minus Touchscreen with Underbody Lighting Reflection Shown

PAINT TOUCH-UPS

Due to the unstable and accident prone nature of any project, small nicks and scratches were a result of transporting the unit to and from the fiberglass manufacturers, the paint shop, Parker facility, etc. To correct or hide the damage, extra paint was collected from the painter. This custom automotive paint was taken to local hardware company and shook to re-mix the color pigments. Hobby/craft brushes were then cleaned and meticulously used to touchup every imperfection found. Figure 71 shows Jessica Hunnicutt correcting and scuff to the ICS from shipping.



Figure 71 - Paint Touch Ups

Section III:

Testing

STEADY-STATE TEMPERATURE AND TIME CONSTANT TEST

The objective of this test is to generate a temperature vs. time plot of the temperature at the cold plate at the nominal operating conditions (500 W heat load, 38% pump speed, and 50% fan speed) in order to obtain the steady-state temperature and the time constant of the system.

PROCEDURE

1. Supply power to the ICS
2. Set the heat load to 500 W.
3. Set the pump speed to 38 %
4. Set the fan speed to 50 %.
5. Start the data logging
6. Wait until temperature at cold plate reaches steady-state.
7. Stop the data logging
8. Graph temperature vs. time plot.
9. Scale-off the x-axis crossing of the initial slope
10. Scale-off steady-state temperature
11. Turn off power supply to ICS

RESULTS

The test results showed that the steady state temperature is about 49°C and the x-axis crossing of the initial slope is about 14 seconds. The ambient temperature was about 22°C during this test. See Figure 72 for charted results of the test.

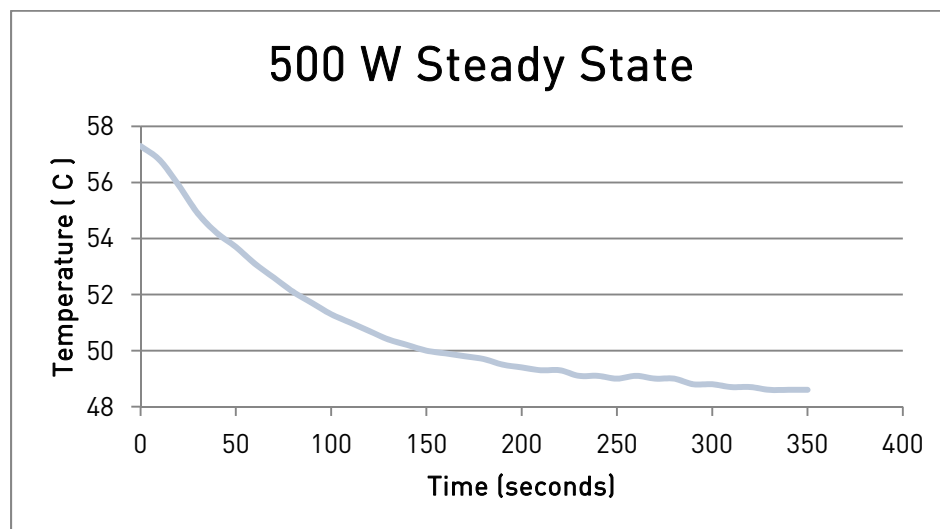


Figure 72 - 500 W at Steady-State

EXTREMES TEST

The objective of this test is to find out how hot or cold the cold plate can get at extreme operating conditions without the fan being on and then with the fan at full speed. This gives an idea of the lowest temperature we can cool the 'electronics' to and the highest temperature the 'electronics' can get up to in our system.

(Note: An electronic safety shut off was implemented in the code so that any measured temperature does not go above 90°C).

PROCEDURE A

1. Supply power to the ICS
2. Select heat load to be 100 W
3. Set pump speed to 14%
4. Set fan to 100%
5. Start data logging
6. Wait 10 minutes or till steady state, whichever is first.
7. Stop data logging
8. Turn off power supply to ICS

RESULTS OF A

The test results showed that the lowest temperature that 'electronics' can be cooled to in our system is approximately 31°C. This is with the lowest heat load and the highest fan speed. See Figure 73 for results.

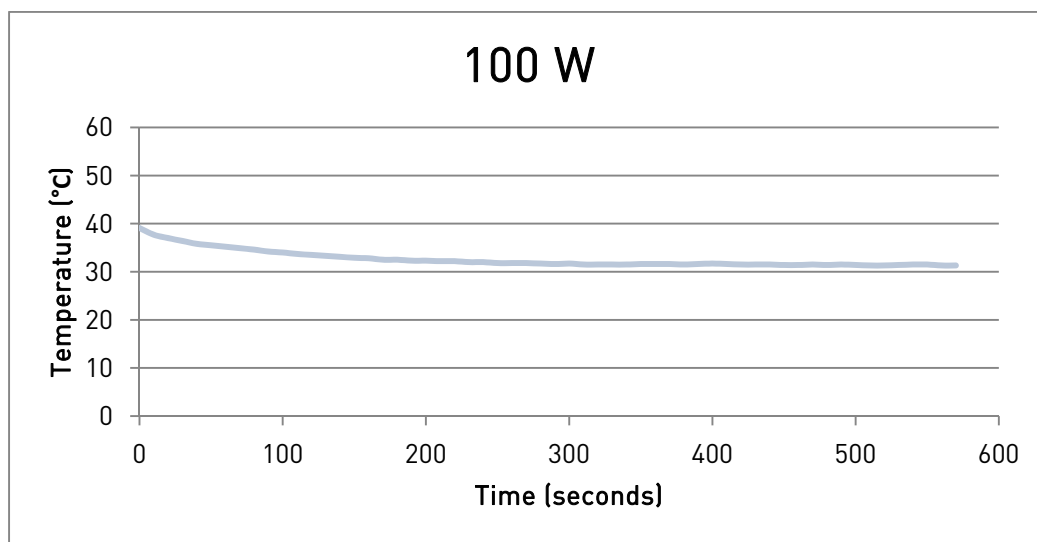


Figure 73 - Extremes Test: 100 W

PROCEDURE B

1. Supply power to the ICS
2. Select heat load to be 1000 W
3. Set pump speed to 64%
4. Set fan to 0%
5. Start data logging
6. Wait 10 minutes or till steady-state or until maximum allowed temperature occurs, whichever is first.
7. Stop data logging
8. Turn off power to the ICS

RESULTS OF B

The test results showed that the highest temperature that 'electronics' can get up to in our system is approximately 90°C; at this point, the safety feature kicks in and turns off the heat and then the temperature starts to drop. See results charted in Figure 74.

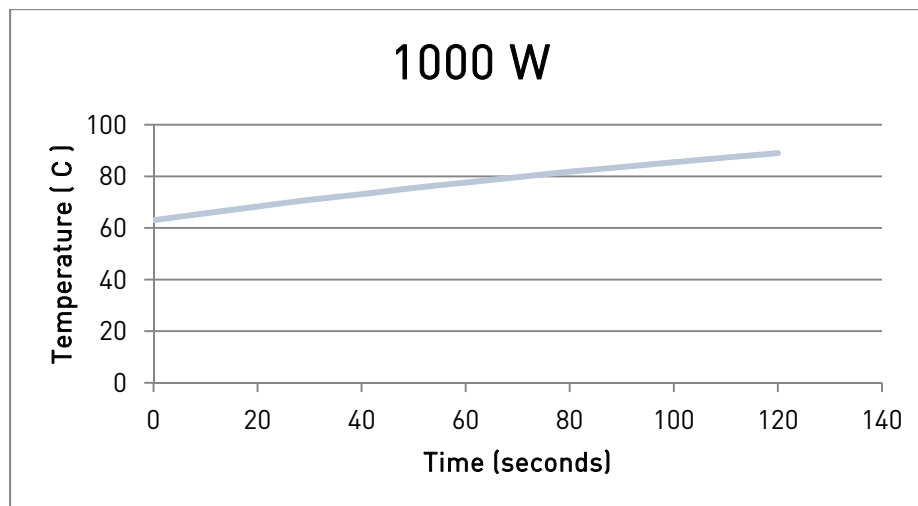


Figure 74 - Extremes Test: 1000 W

WORKING CONDITIONS TEST

The objective of this test is to generate a plot of the fan control voltage versus temperature at the cold plate for each heat load. Using thermodynamic theories, the pump speed that corresponds with an exit refrigerant quality of 0.7 (70% vapor) was found for each heat load and the pump was manually set to this value. Lines were fit through the derived curves and the equations for fan steady-state speed (voltage) at each heat load were extracted.

PROCEDURE

1. Supply power to the ICS
2. Set the heat load to 1000 W
3. Set the fan to 10 V (100%).
4. Wait 5 minutes or until the system reaches steady state (or goes over 80 degrees [C]).
5. Record the heat input, fan speed (V), pump speed (%), and the temperature at the cold plate.
6. Reduce the fan speed by 1 V (10%).
7. Repeat steps 4-6 until a fan voltage of 1 V has been tested.
8. Reduce the heat input by 100 W.
9. Repeat steps 3-7 until each heat load has been tested.
10. Turn off the ICS.

RESULTS

From Figure 75 below, it can be seen that at higher fan speeds the temperature at the cold plate decreases for each heat load from 100 W to 1000 W. The equations derived from each heat load curve were used in designing the control system and they can be found in the Section I: Detailed Conceptual Design in Table 11. At 100 W, the temperatures at the cold plate are much lower (about 30 degrees lower) than the temperatures at the cold plate when the heat load is 1000 W. The ranges of the temperature at the cold plate for each heat load can also be deduced from the graph. For instance, from the graph, we can tell that one cannot cool a 100 W heat load below 30°C and we cannot cool a 1000 W heat load below 65°C, because at the highest fan speed, that is the lowest temperature that can be achieved.

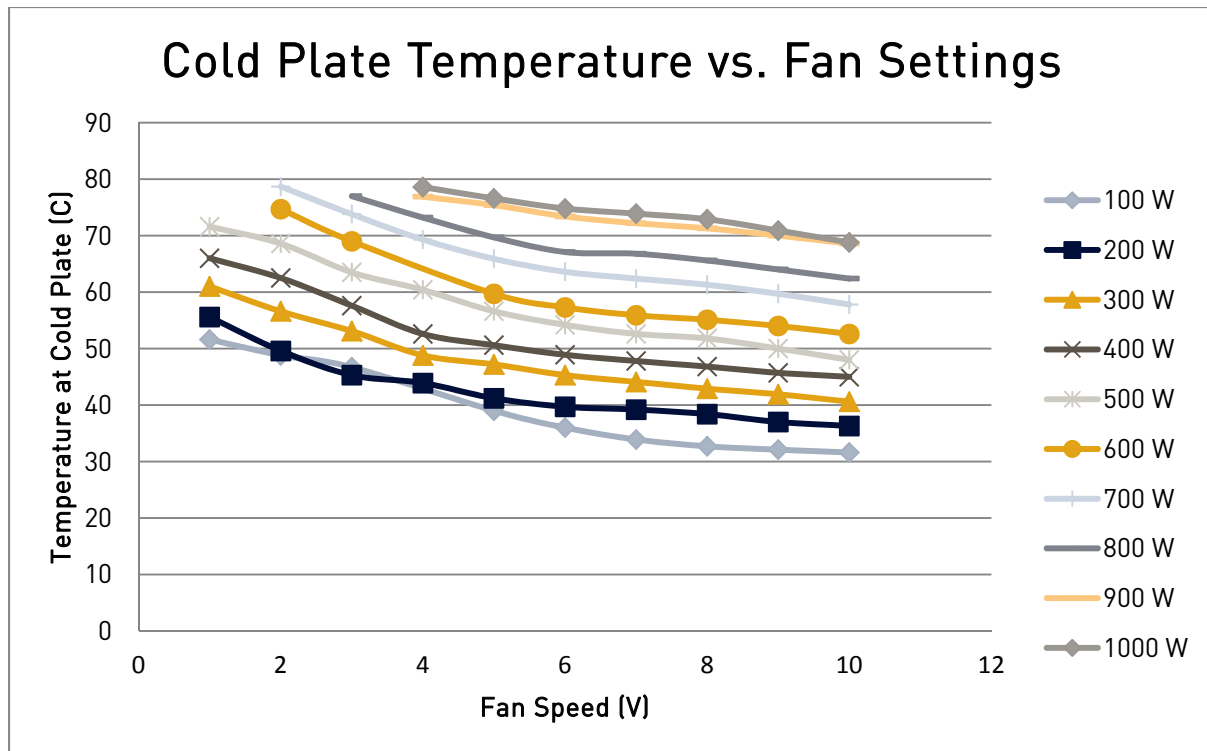


Figure 75 - Summary of Cold Plate Temperatures with Given Fan Speed and Heat Load

CONTROL SYSTEM OPERATION TEST

The objective of this test is to make sure that the control system works properly, i.e. the desired temperature at the cold plate is reached within 1°C. Different combinations of heat load and desired temperature were selected making sure that the whole range from 100 W to 1000 W was covered. All heat loads were tested with different randomly chosen desired temperatures. Also, the heat loads were done in random order to make sure that the order of the tests was not a factor in the results since in the final application the order of customer inputs would be random.

PROCEDURE

1. Supply power to the ICS
2. Select heat load
3. Select desired temperature
4. Wait till the temperature at the cold plate is within 1 C of desired temperature
5. Choose next set of inputs
6. Repeat steps 2-5 until all heat loads have been covered
7. Turn off power to the ICS

RESULTS

The first test done had input values of 500 W for heat load and 60 °C for desired temperature. The graph below, in Figure 76, shows the temperature at the cold plate versus time. The temperature at the cold plate is initially about 55 °C and since this is below the desired temperature, the fan is initially off so the cold plate can heat up. Once the temperature at the cold plate exceeds 60°C, the fan turns on and starts to cool down the temperature at the cold plate. This is the reason for the initial peak on the graph. After a while, the fan regulates itself and gets the temperature at the cold plate to settle to about 60.6°C which is within 1°C of the desired temperature of 60°C.

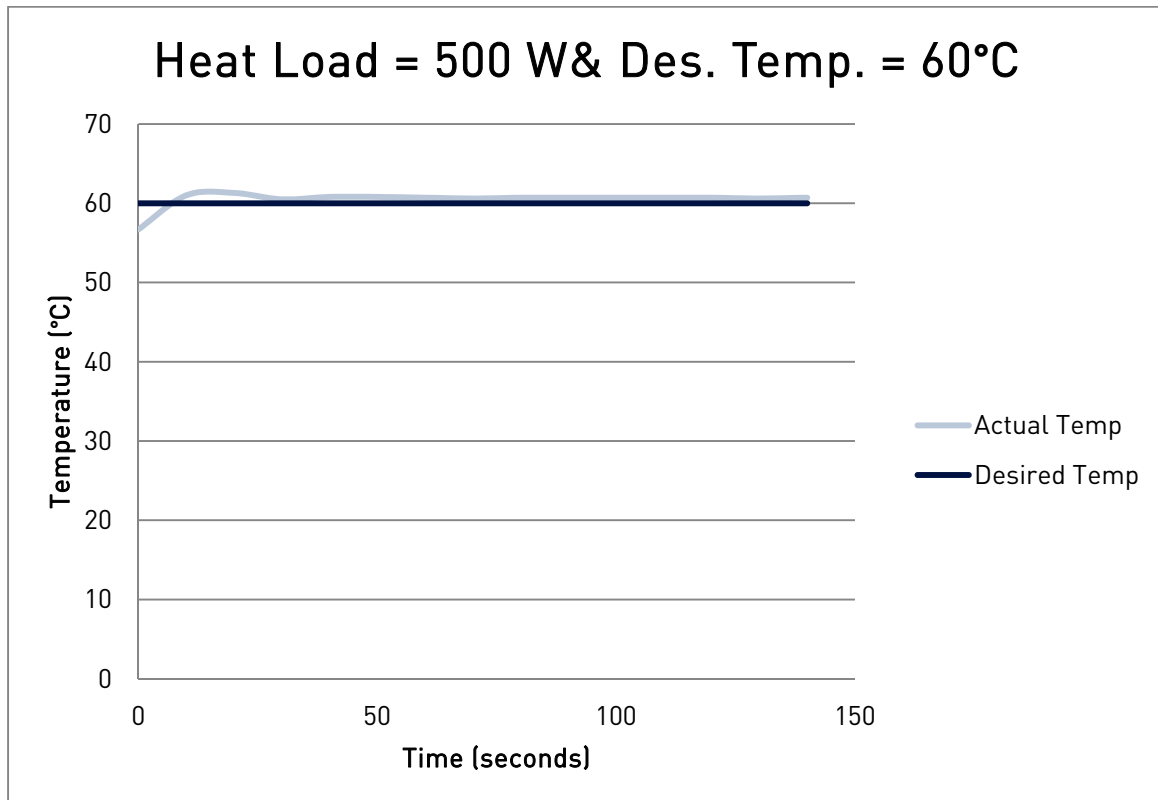


Figure 76 - Heat Load of 500 W and Desired Temperature of 60°C

The next test had input values of 200 W for heat load and 70°C for desired temperature. The graph below in Figure 77, shows the temperature at the cold plate versus time. The temperature at the cold plate is initially about 58°C and since this is below the desired temperature, the fan is initially off so the cold plate can heat up. Once the temperature at the cold plate exceeds 70°C, the fan turns on and maintains the temperature at the cold plate at around 70°C. In this graph, there is no overshoot in temperature, there is a smooth transition to the desired temperature and the temperature is maintained.

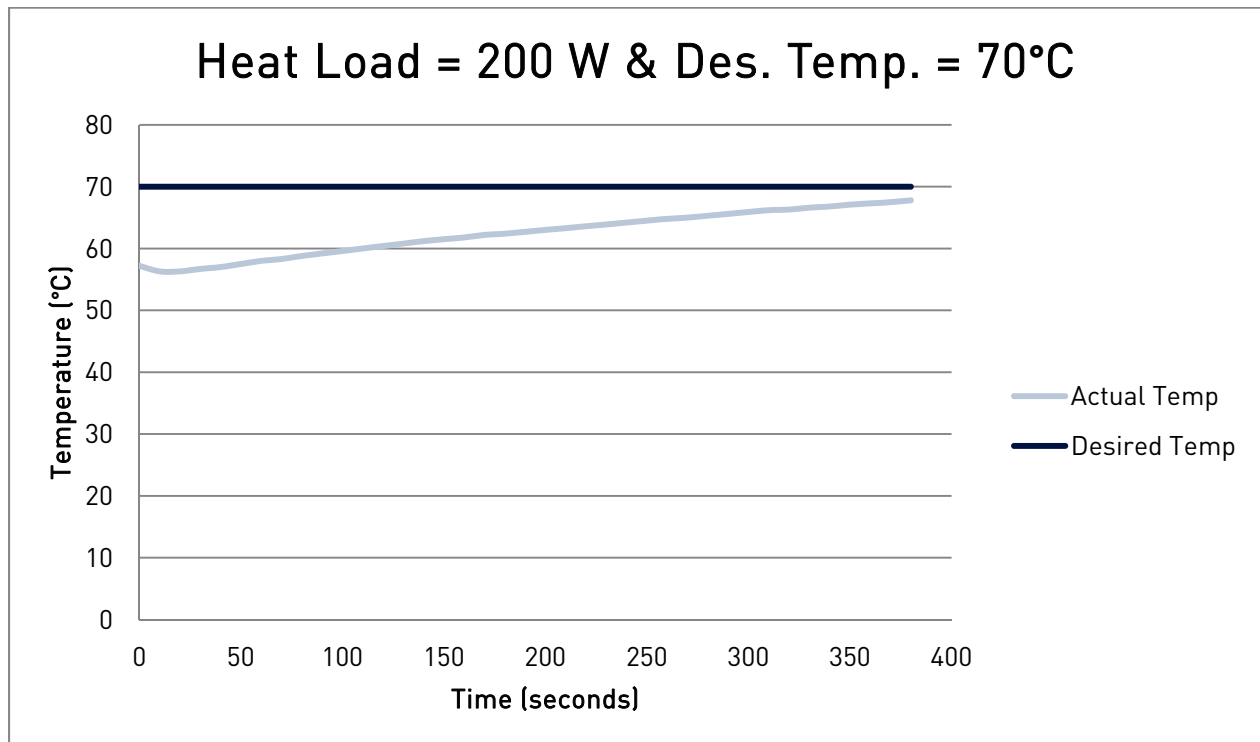


Figure 77 - Heat Load of 200 W and Desired temperature of 70°C

The next test had input values of 500 W for heat load and 60°C for desired temperature again. This test was repeated, because we wanted to find out if the system would still reach the desired temperature even if the initial temperature at the cold plate was higher than the desired temperature as opposed to the previous time when the initial temperature was 55°C. The graph below in Figure 78 shows the temperature at the cold plate versus time. The temperature at the cold plate is initially about 65°C and since this is above the desired temperature, the fan is immediately turned on in order to cool the cold plate. This happens, but then the temperature at the cold plate starts to increase again to about 71°C. This is due to the refrigerant in the cold plate losing its two-phase cooling effect, because the fan was at the highest speed thereby causing the pressure of the refrigerant to drop significantly. Eventually, when the refrigerant is back in the two-phase region (at about 2 minutes from the start of the test), the temperature at the cold plate settles to 60°C. Therefore, the desired temperature was achieved, but it just took a longer time and a curvy route.

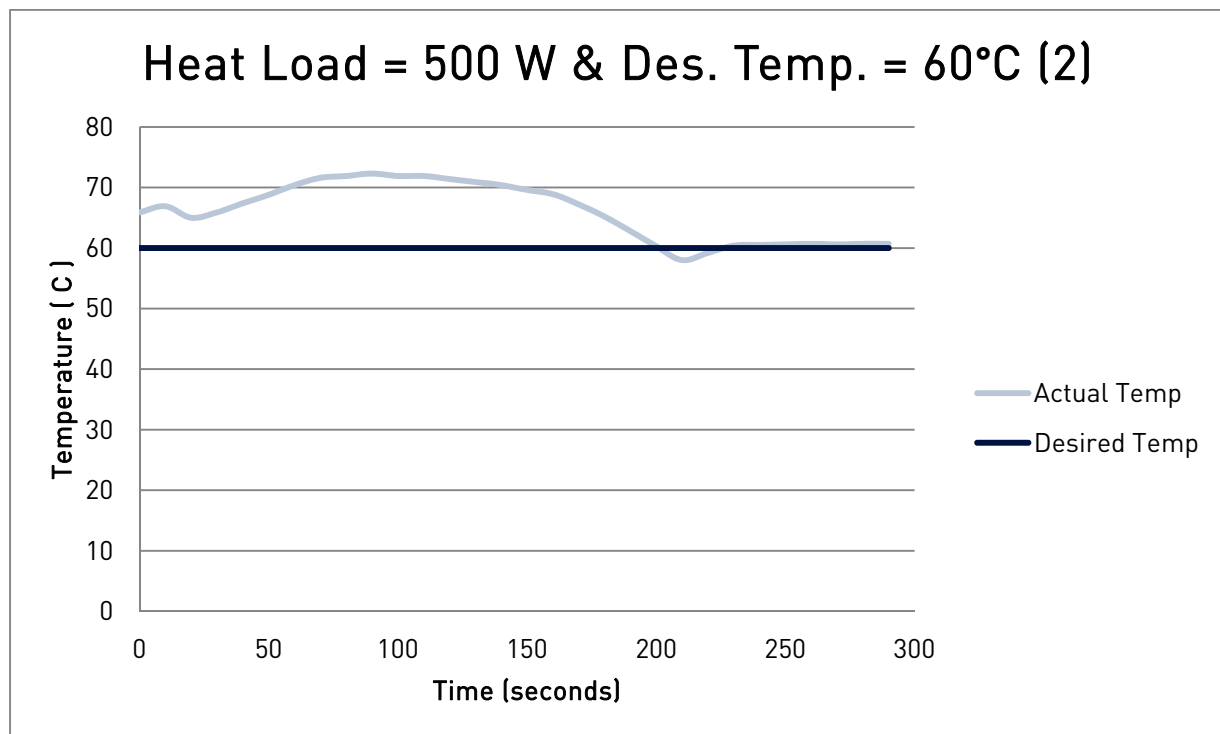


Figure 78 - Heat Load of 500 W and Desired Temperature of 60°C (2)

The next test had input values of 1000 W for heat load and 75°C for desired temperature. The graph below in Figure 79 shows the temperature at the cold plate versus time. The temperature at the cold plate is initially about 65°C and since this is below the desired temperature, the fan is initially off so the cold plate can heat up. Once the temperature at the cold plate exceeds 75°C, the fan turns on and starts to cool down the temperature at the cold plate. This is the reason for the initial peak on the graph. After a while, the fan regulates itself and gets the temperature at the cold plate to settle to about 74.3°C which is within 1°C of the desired temperature of 75°C. This happened within 40 seconds.

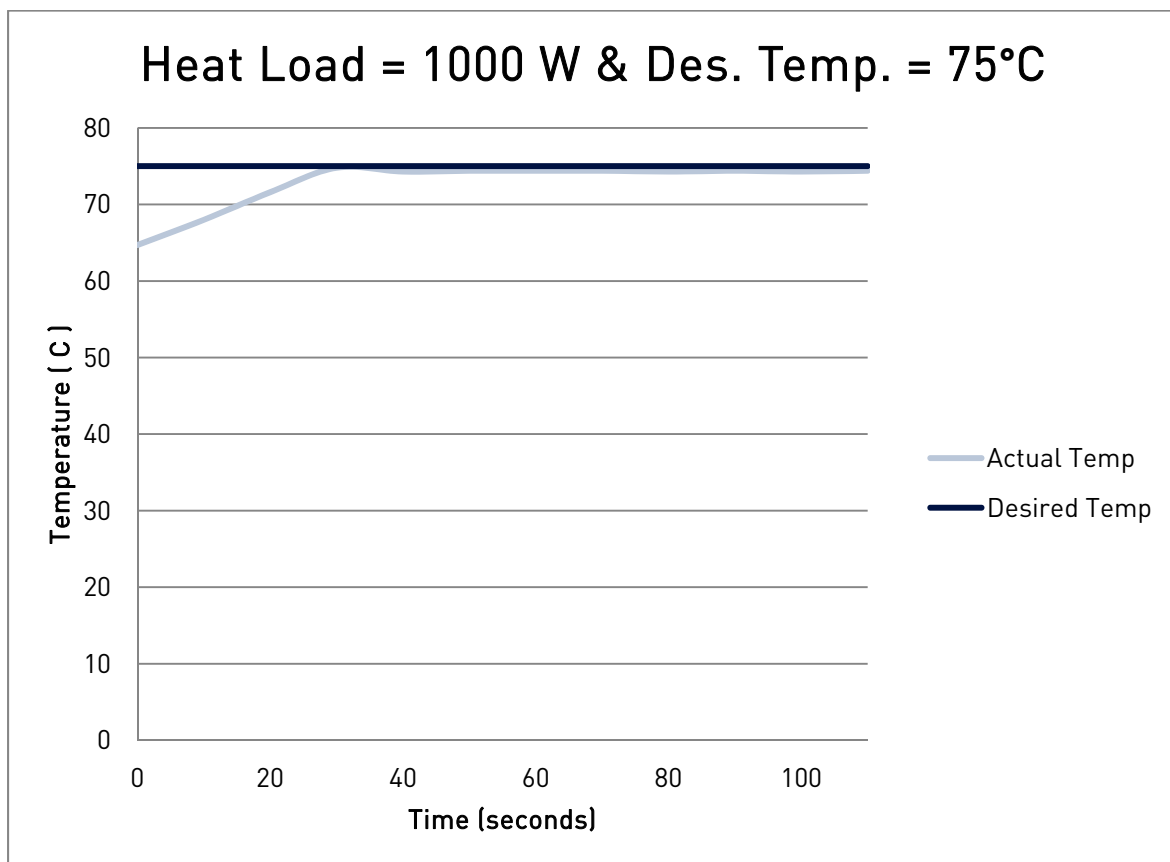


Figure 79 - Heat Load of 1000 W and Desired temperature of 75°C

The next test had input values of 400 W for heat load and 65°C for desired temperature. The graph below in Figure 80 shows the temperature at the cold plate versus time. The temperature at the cold plate is initially about 68°C and since this is above the desired temperature, the fan is immediately turned on so the temperature at the cold plate can reduce. There is undershoot in the graph, because the fan speed was initially too high and cooled the cold plate below the desired temperature. When the fan speed reduced, the temperature at the cold plate increased again and settled at roughly 65°C.

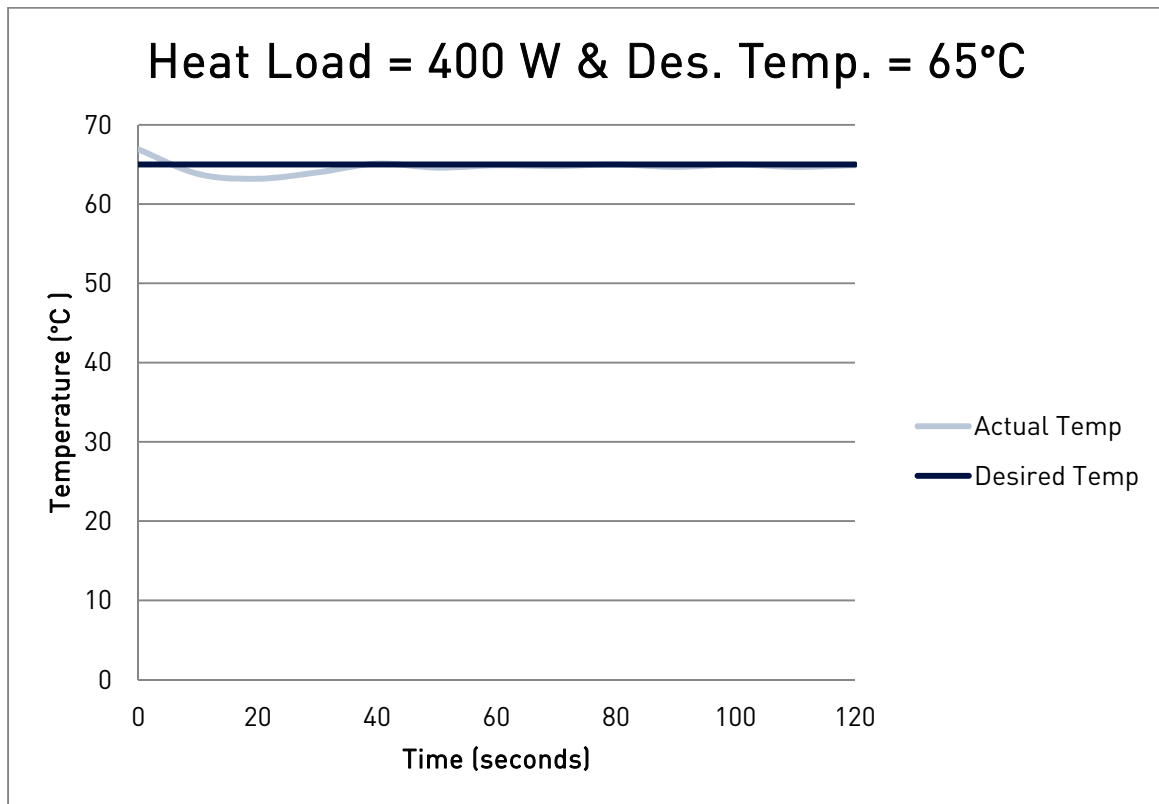


Figure 80 - Heat Load of 400 W and Desired Temperature of 65°C

The next test had input values of 700 W for heat load and 60°C for desired temperature. The graph below in Figure 81 shows the temperature at the cold plate versus time. The temperature at the cold plate is initially about 63°C and since this is above the desired temperature, the fan is immediately turned on so the temperature at the cold plate can reduce. When the fan speed settled to its final value, the temperature at the cold plate ended up being a little lower than 59°C. This does not meet our requirement of within 1°C, but we believe this has to do with different environmental conditions such as ambient temperature and initial temperature of the cold plate.

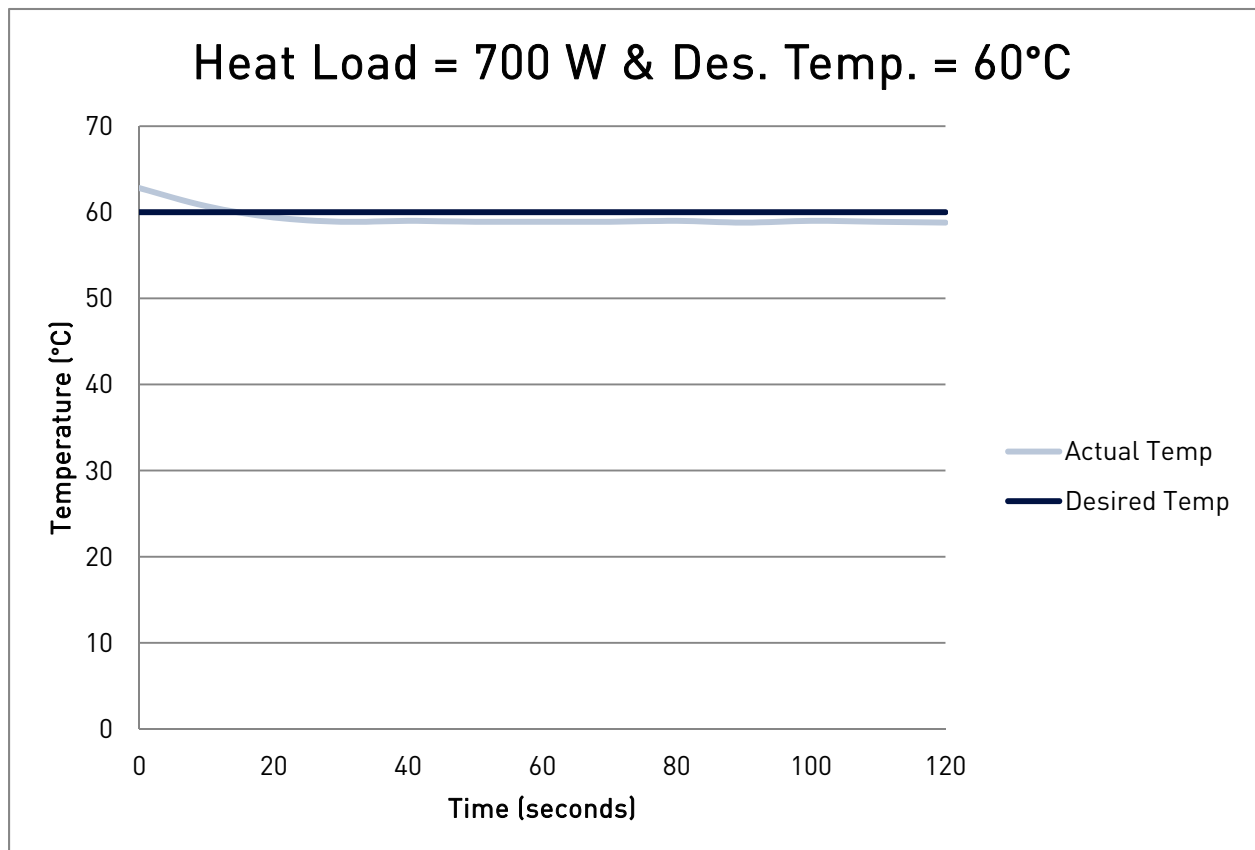


Figure 81 - Heat Load of 700 W and Desired Temperature of 60°C

The following figures (Figures 82 to 87) show the results of several other test points that were chosen. In each case, the desired temperature was always met to within 1°C. This shows that the control system designed is capable of achieving an input desired temperature within the temperature range possible for each heat load.

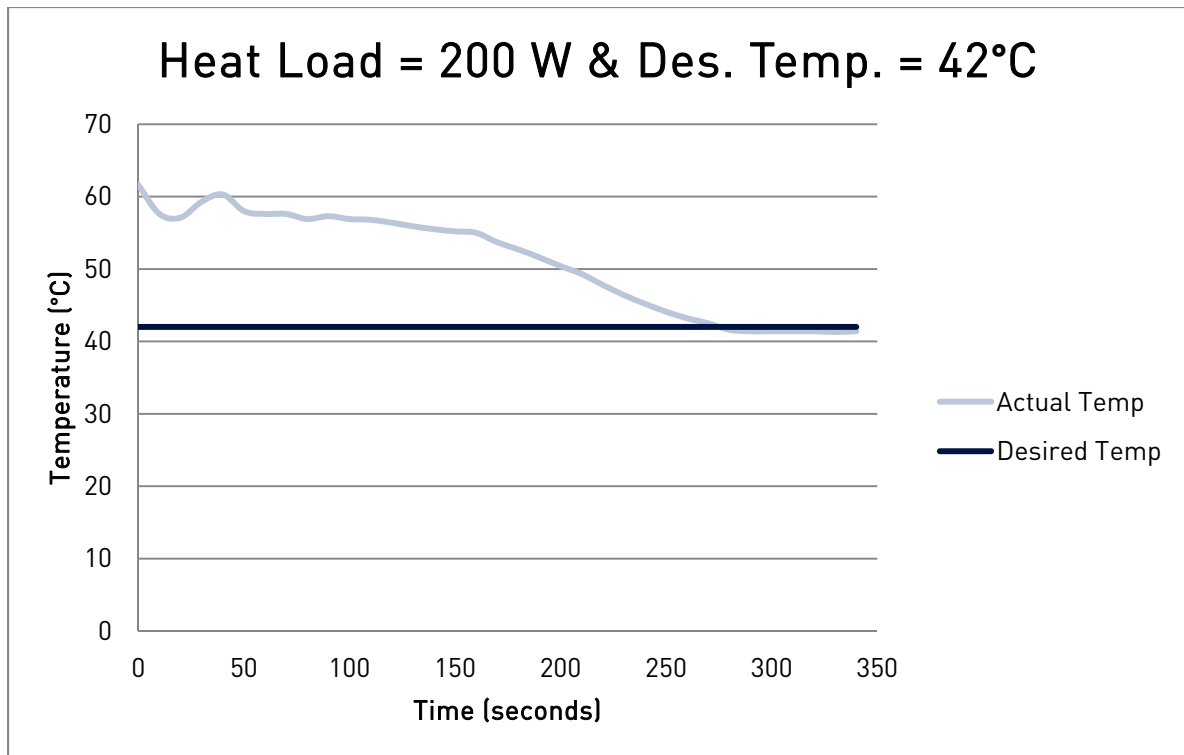


Figure 82 - Heat Load of 200 W and Desired Temperature of 42°C

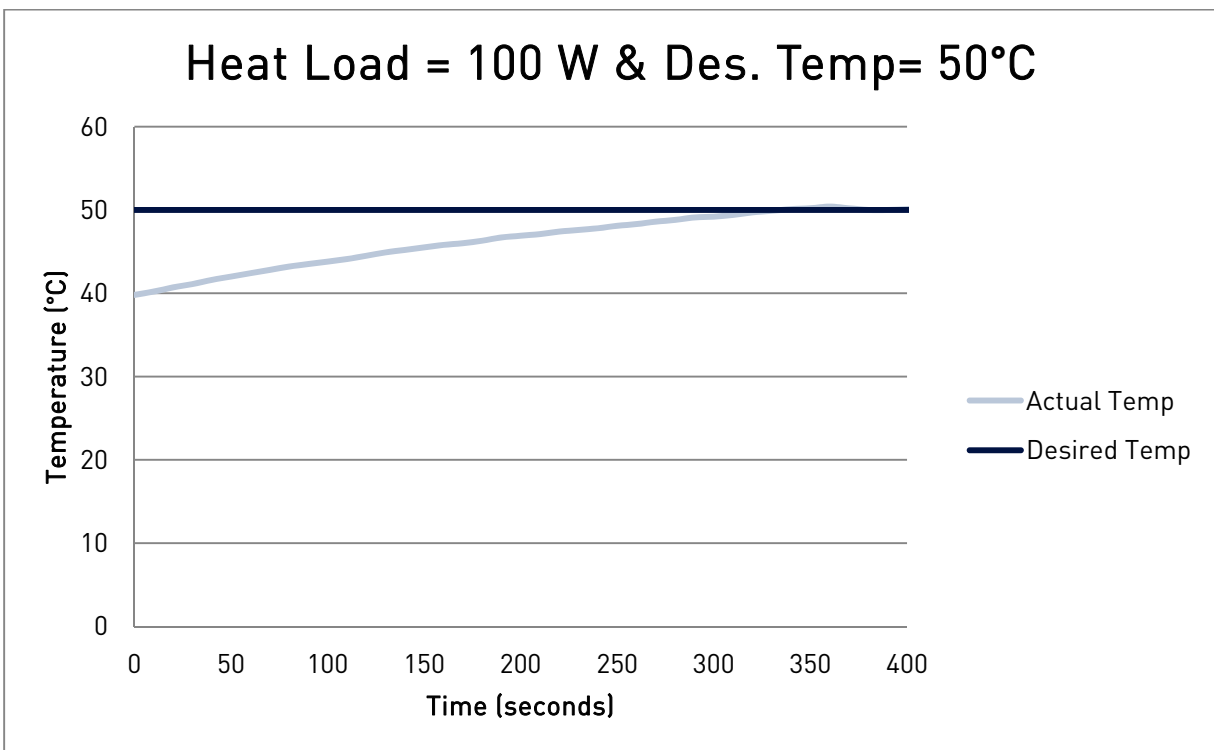


Figure 83 - Heat Load of 100 W and Desired Temperature of 50 °C

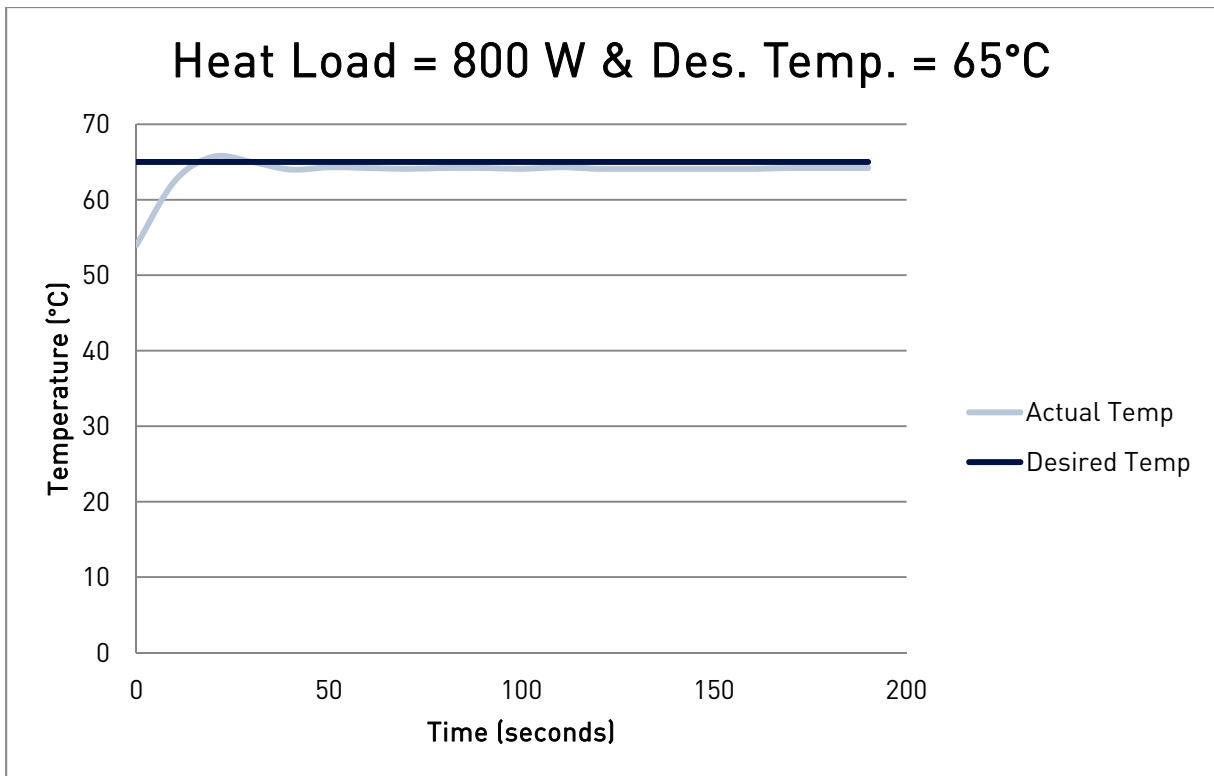


Figure 84 - Heat Load of 800 W and Desired Temperature of 65°C

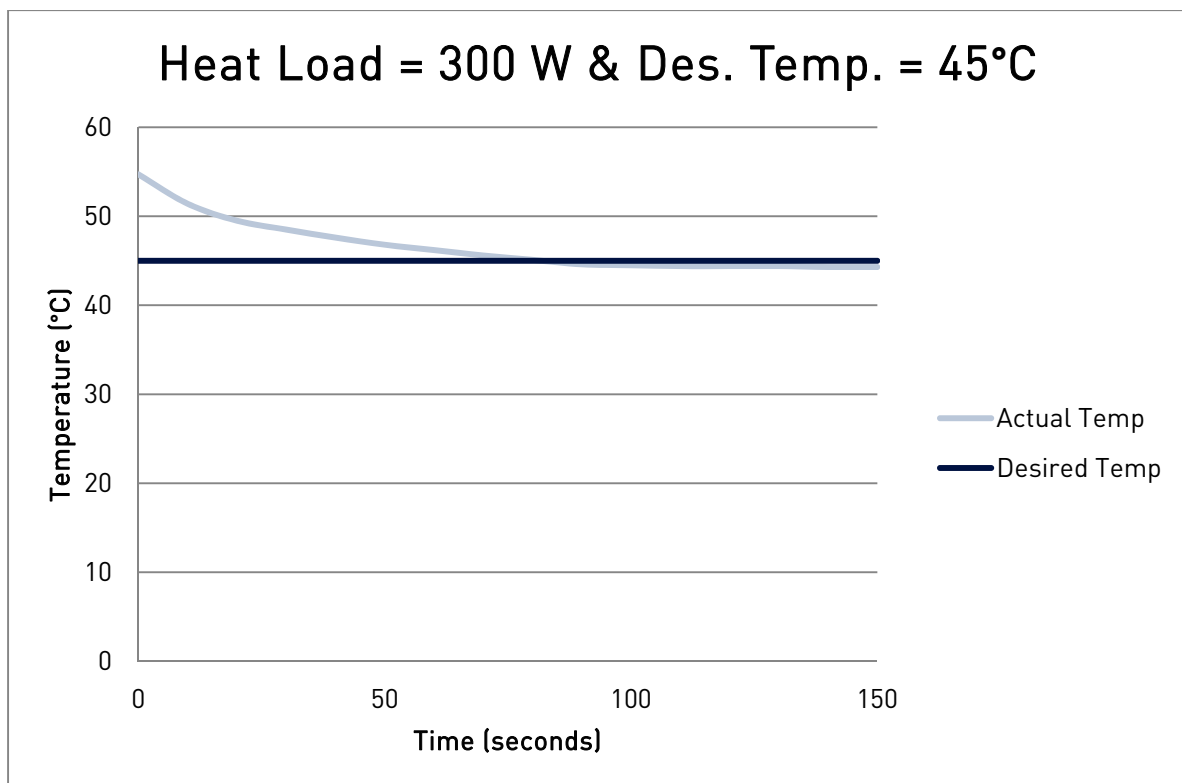


Figure 85 - Heat Load of 300 W and Desired Temperature of 45°C

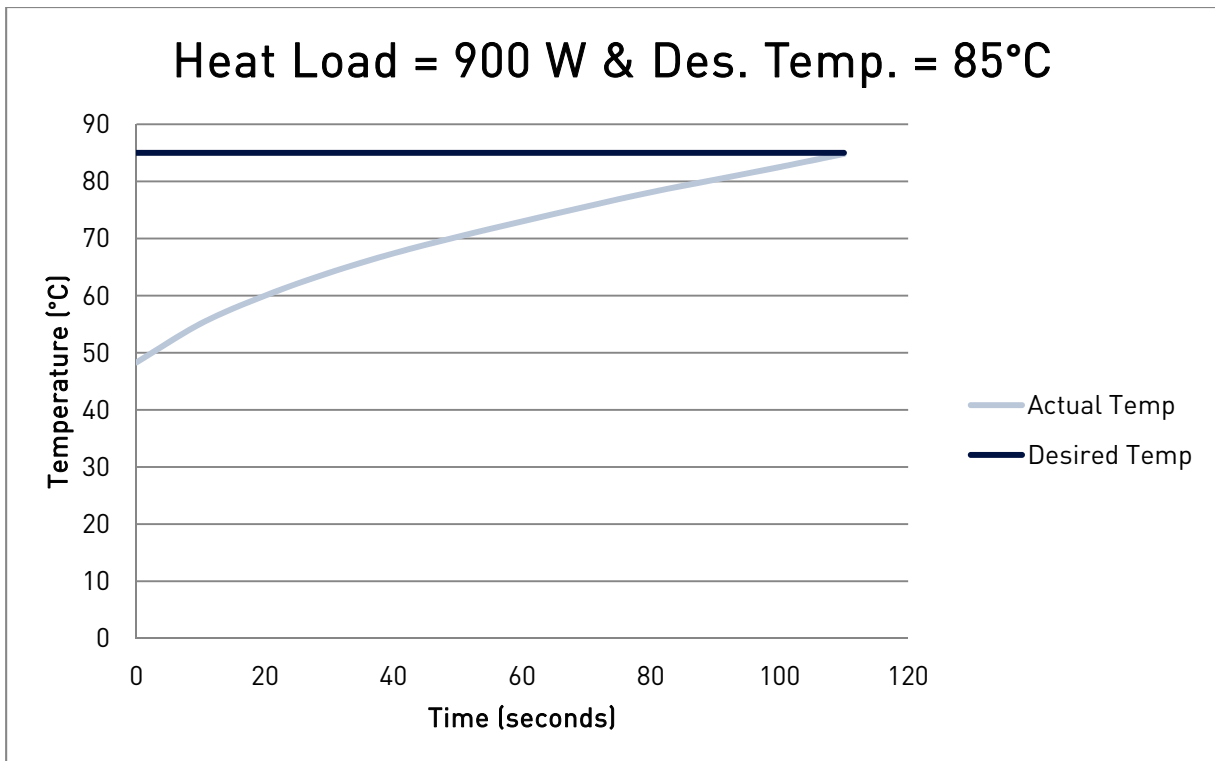


Figure 86 - Heat Load of 900 W and Desired Temperature of 85°C

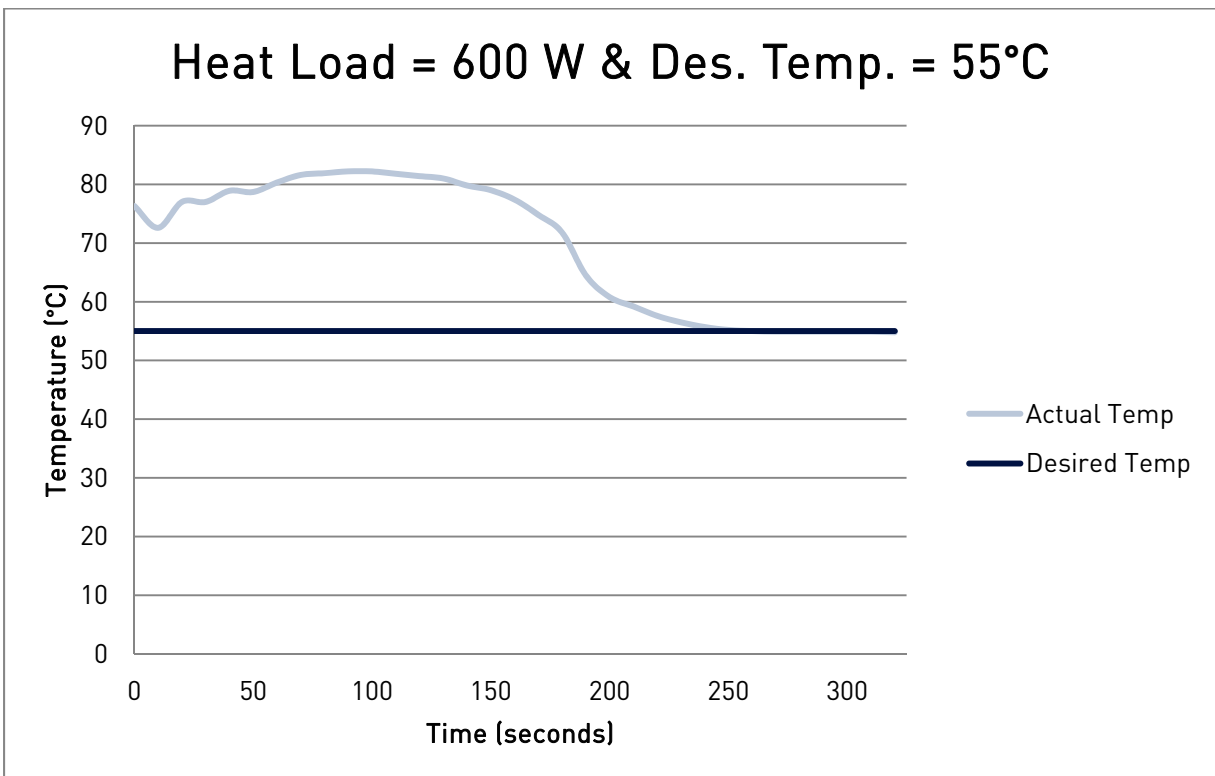


Figure 87 - Heat Load of 600 W and Desired Temperature of 55°C

EASE OF OPERATION TEST

The objective of this test is to figure out how easy it is for users to navigate the GUI. Ease is measured by how many 'use' questions are asked during a trial run. A 'use' question is a question that tries to figure out how to do a particular function on the GUI.

PROCEDURE

During a trial run, 0-3 questions means easy; 4-6 questions means medium; and 7-10 questions means difficult. Five students were randomly selected to interact with the ICS and Figure 88, below, shows the result of the test.

RESULTS

As the figure shows, only one person out of the five asked more than one 'use' question. This shows that the GUI is easy to use.

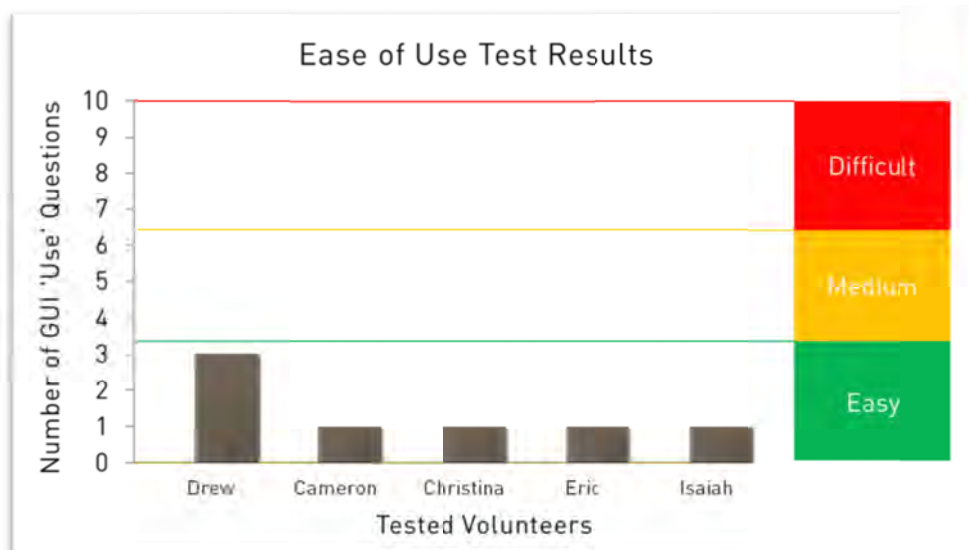


Figure 88 - Ease of Use Test Results Chart

CONTROL DESIGN MODIFICATION

A problem was discovered during testing of the control system that required an innovative solution to fix. The team noticed that when the user was going from one trial at a higher heat input and higher desired temperature to another trial with a lower heat input and lower desired temperature that the system would become temporarily unstable. This instability was a result of the refrigerant leaving the two-phase region and vaporizing. See the transient response of the ICS going from 900 W at 80°C to 600 W at 55°C before the control system modification in Figure 89. Note the instability that occurred when the two-phase refrigerant composition was lost.

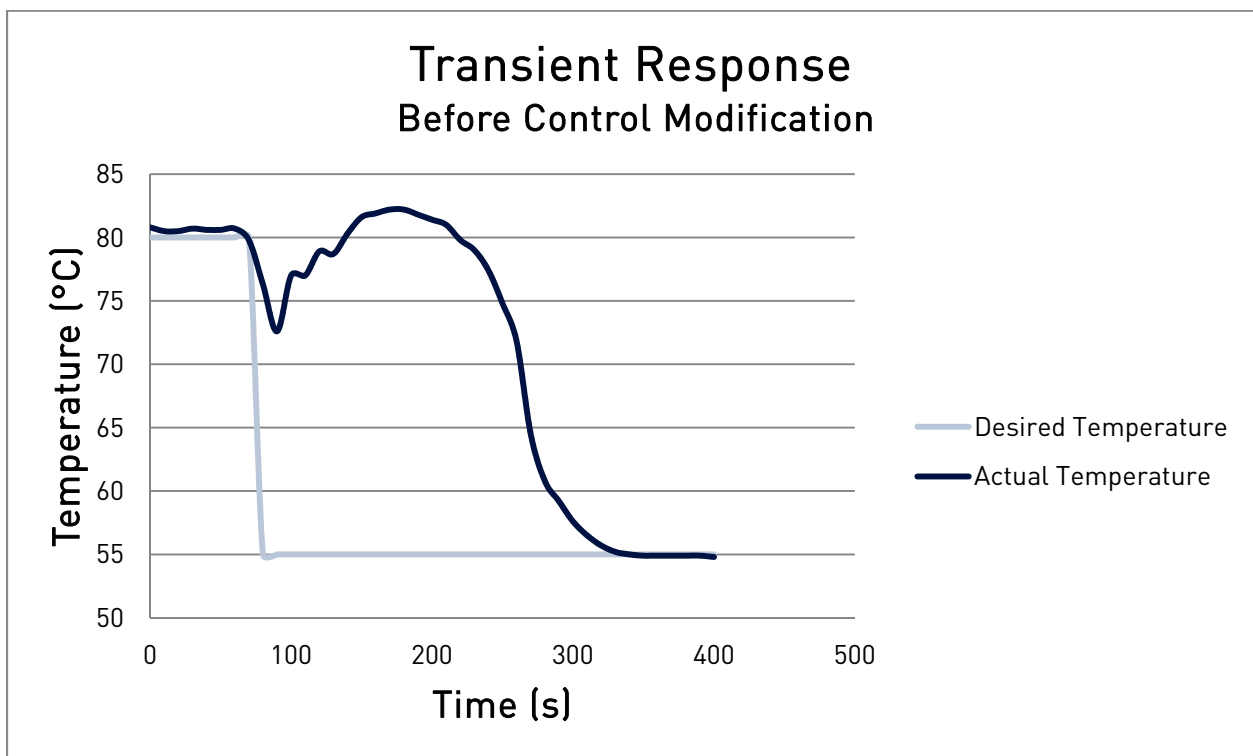


Figure 89: Before - Transient Response, 900 W @ 80°C to 600 W @ 55°C

The refrigerant is able to enter a superheated state during the transient operation when going from a higher heat-load and high temperature to a lower heat load with a low temperature. The pump immediately slows its speed per the lower heat-load pump control. However, since the system is still running at a high temperature, the pump is not running fast enough to get the refrigerant over the cold plate before it completely vaporizes. To solve this problem the design-team agreed to re-design the pump control to account for this transient operation.

To solve this problem, the pump speed increases when the system changes from a high temperature to a low temperature while the fan is operating at 100%. This higher pump speed forces the refrigerant through the cold plate fast enough to prevent it from vaporizing before the exit. See the transient response of the ICS going from 900 W at 80°C to 600 W at 55°C after the control system modification in Figure 90.

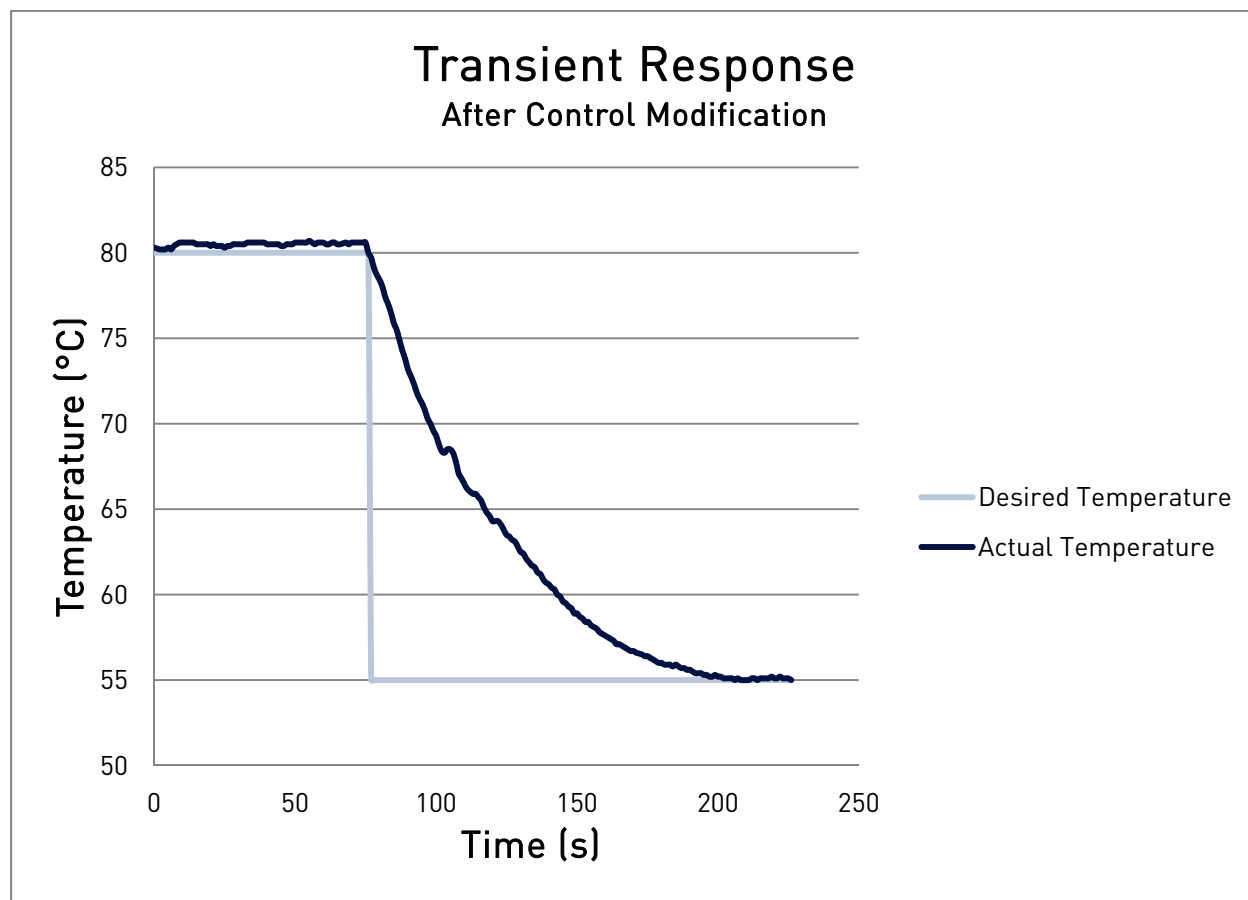


Figure 90: After - Transient Response, 900 W @ 80°C to 600 W @ 55°C

Compare Figure 89 with 90; note the time it takes to achieve the desired temperature is much less after the modification. The control system was tested rigorously after the modifications were made in order to ensure performance across the heat and temperature inputs, see Figure 91. Note the absence of unstable peaks like in Figure 89; the two-phase refrigerant composition was not lost.

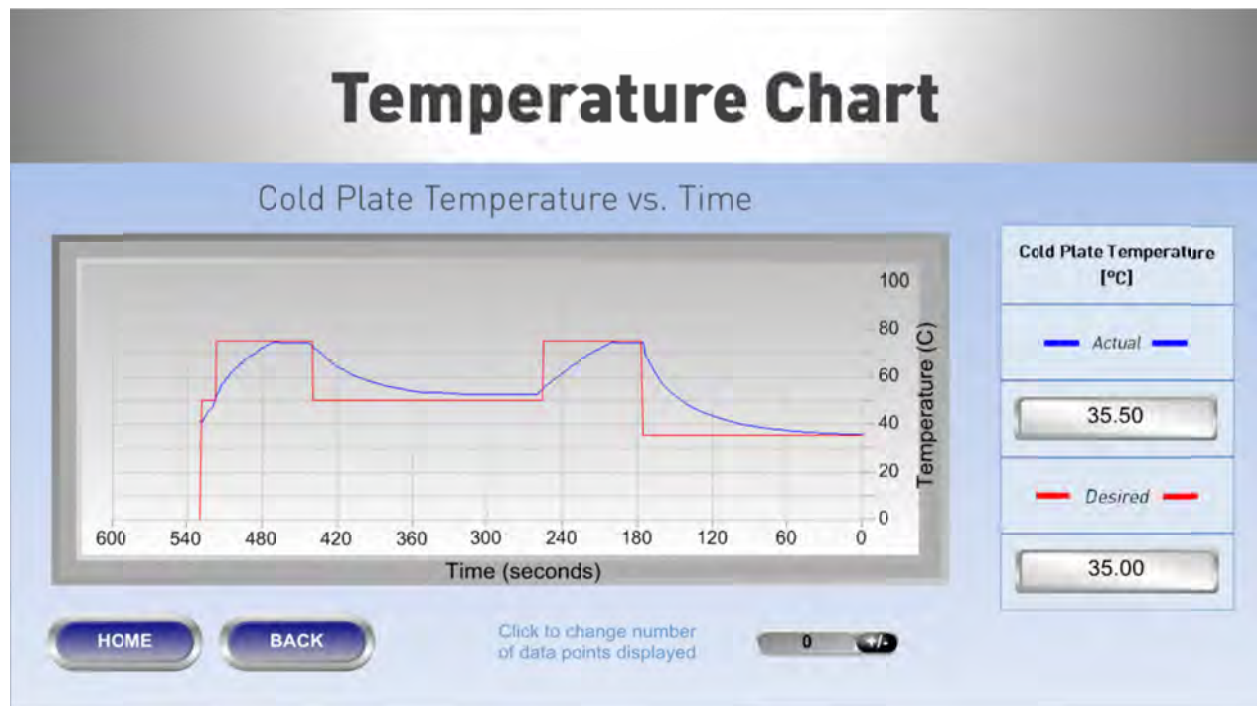


Figure 91 - Screen-Shot of Modified Control System Test

Section III:

Evaluation & Recommendations

In the evaluation of the ICS, it was necessary to determine if the device adequately meets each of the requirements and specifications listed in the problem statement. The problem statement was created by the team prior to design of the ICS. The following subsections will examine the performance of the ICS in regard to each of these requirements and specifications as well as listing the recommended course of action if a future ICS was created.

PHASE COMPOSITION

The ICS was designed so that refrigerant would change phase as it passes over and cools the cold plate. It was specified that this two-phase process must be visible, and the refrigerant must not enter a superheated state. The desired quality at the exit of the cold plate was set at 0.70. Testing concluded that the ICS meets the first part of this requirement. It is easy for an observer to see the change of state of the refrigerant as it passes over the cold plate. The second part of this requirement was also met. After the control system was completed, there was no observed case in which the refrigerant was completely vapor at the cold plate's outlet. Due to the design of our cold plate, the quality is generally between 0.35 and 0.5 at the cold plate's outlet, which is significantly lower than the specification of 0.70. This exit quality is lower than specified because the pump is required to run faster than it was originally designed for to prevent the unstable condition described in the "Control Design Modification" section of this report.

Recommendation: In future versions of the ICS, it may be desired to use a smaller cold plate or develop a more intelligent pump-control to prevent the unstable state described in the "Control Design Modification" section of this report. If these issues were fixed, the system could run at a higher quality, which would yield more efficient cooling.

FAN SPEED

A second requirement was that the ICS had to have a variable fan speed that was controlled by feedback from the operating conditions.

Recommendation: This requirement was met. There is no further recommendation.

MAXIMUM WEIGHT

The ICS was not to exceed more than 500 lbs. This specification was set so that the display could be moved easily. The ICS unit was weighed at 363 lbs on an industrial scale. It also proved to be easily transportable.

Recommendation: This specification was met. There is no further recommendation.

EXTERIOR OPERATING TEMPERATURE

The exterior temperatures of all of the parts of the ICS were not to be hot to the touch. While the exterior aluminum of the cold-plate assembly and the copper of the accumulator can get fairly warm, there was never a point in the testing where the surfaces became uncomfortably hot to touch with a hand.

Recommendation: If a device similar to the ICS is created and is designed to run at temperatures higher than what the current ICS can run at, the surfaces may become too hot to touch. It would be recommended to either situate the components in a way in which the operator cannot touch them, or add an outer insulating material so that the metal surfaces are guarded and untouchable.

PERFORMANCE

It was determined that the ICS must be able to deal with heat loads from 100 W to 1000 W, and it must be capable of cooling the source to within 1°C. The ICS was designed to meet both of these criteria. During testing, it proved to cool the heat source within the required accuracy for the entire range of heat loads specified. The system also proved to cool the system to a specified temperature within the required 3 minute time interval. The system actually cooled slightly faster than the theoretical calculations. Figure 92 shows the actual system response compared to the theoretical response in the mathematical model.

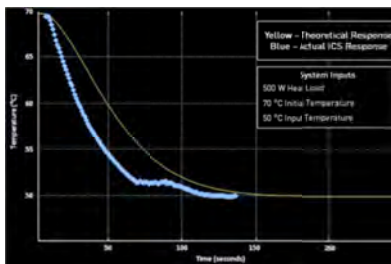


Figure 92 - Comparing Theoretical Response to Actual Response

Recommendation: While the requirement was met, the range of temperatures that the heat source can be held at steady-state at, especially in the higher heat-load cases (+800 W), is not large. For example, the device can bring the source to between 70 °C and 85 °C at 1000 W. This is only a range of 15 °C. The team's recommendation would be to use either a better cold plate, a better condenser, or a better fan so the ICS would be capable of cooling a 1000 W source to cooler than 70 °C, or to design the ICS so that it is able to operate at higher temperatures.

INSTRUMENTATION

The ICS was required to use thermocouples and pressure sensors to measure thermodynamic data of the refrigerant. Using this information, it was to shut itself down when the pressure or temperature exceeded the limits of operation. It was also required to be able to export data to a PC.

Recommendation: Each of these criteria was met, and there are no further recommendations.

HUMAN INTERACTION

The ICS was to have an appropriate amount of human interaction. This included the ability to set a heat load, and also the ability to set an achievable temperature for the system to cool the source to. These options are available for the user to adjust in the GUI. The user must also have different viewing options so he or she can observe several different types of data. This parameter was adequately achieved.

Recommendation: In the current, completed version of the ICS, the user does not have the ability to manually adjust the fan. It is only adjusted by the automatic control system. In future versions, it may be desirable to allow it to be manually adjusted in addition to having it automatically controlled. An additional, manual button could be added to the GUI. Several adjustments would have to be added to the ICS control to accommodate this option.

GENERAL SIZE

It was required that the ICS must be small enough to fit through a standard door. This was achieved.

Recommendation: The ICS team would recommend making the depth of the unit bigger for stability reasons

REFRIGERANT

Parker specified that a refrigerant must be used as the working fluid. R134a was the refrigerant used in the ICS.

Recommendation: Due to its low saturation pressures, it would also be the recommended refrigerant to use in future versions.

PUMP SPECIFICATION

It was specified that the ICS use a pump that was similar to other Parker two-phase cooling systems. The ICS uses a 1000 mL/min pump that is consistent with the requirement.

Recommendation: The same pump is recommended on future versions.

TOUCHSCREEN

A touchscreen was to be used to allow an operator to control the ICS. In the ICS, this was achieved. A large HP touchscreen was used in conjunction with InteractX software. The touchscreen displays thermodynamic information per the project requirements.

Recommendation: The team would recommend the use of a touchscreen in future versions. While the cost is high and the programming of the GUI takes up a significant amount of time, it definitely adds to the aesthetic appeal of the ICS. It also allows for an organized way to control the ICS and also display information.

COLD PLATE

A copper cold plate was to be designed to evenly disperse the refrigerant flow through micro-channels. The cold plate in the ICS does an adequate job at this. During operation, it is evident that the refrigerant is flowing through each micro-channel fairly evenly.

Recommendation: There is no further recommendation.

HEAT EXCHANGER

A heat exchanger was to be designed or selected to reject heat from the system. In the ICS, a refrigerant-to-air condenser was selected. The condenser coil was sized to fit a single, controllable fan.

Recommendation: This type of heat exchanger would be recommended in future versions.

COST

The two ICS units together were to cost no more than \$30,000. This cost-limit was exceeded, but no more than 10% of the overall cost. In future versions, it may be desirable to reduce cost. If this is the case, a significant amount of the cost could be reduced by not using a custom fiberglass shell, or reusing the current shell.

Recommendation: The ICS team recommends quotes be received from more suppliers/manufacturers during the procurement process to reduce costs.

LOW MAINTENANCE

The ICS was to require as little maintenance as possible. At the time of this report, the ICS has not yet required maintenance.

Recommendation: The team's recommendation is to re-evaluate this requirement at a future date.

AESTHETICS

The ICS was to be as aesthetically pleasing as possible because it will often be displayed in public places and the overall appearance represents IPFW and Parker Hannifin. The team believes that the ICS is adequately aesthetically pleasing. During construction and testing, many observers commented on the device, leading the designers to believe that it is able to draw interest in people as they pass.

Recommendation: A fiberglass shell, either a new design or the current design, would be recommended again in future versions of the ICS.

SAFETY

The ICS was required to be safe to all operators and observers. This required the unit to not have sharp edges, not blow overly hot air out the front, be unable to burn someone, and be vertically stable. Each of these requirements was met.

Recommendation: While the unit is sufficiently stable, it is recommended that the base be designed to be larger in future versions to add to the stability. The unit is not easy to tip over, but it can be done if an observer would purposely or accidentally add a horizontal force near the top of the unit.

ENVIRONMENTAL INTEGRITY

The unit was to have a leak rate of less than 0.1 ounces per year. Using very precise leak-checking equipment, the unit was carefully tested for leaks. It was determined by an expert that the unit does not leak more than 0.1 ounces per year, which is the sensitivity-limit of the equipment.

Recommendation: There is no further recommendation.

Conclusion

In conclusion, the ICS system is visually striking and attracts the interest of prospective customers at trade shows, employees at the Parker Hannifin - New Haven facility, and students at IPFW. Once people are interested in the display unit, the ICS allows the user to adjust the heat load and desired temperature of the heat source. The automatic control system then accurately brings the electronic device we are cooling to the desired temperature in a minimal amount of time. They are able to easily navigate through the GUI on the touch screen to see different properties of the system and information on the two-phase cooling technology. The ICS team believes that the system has met and exceeded the expectations of the desired display unit for Parker Hannifin's Precision Cooling Business Unit. Parker Hannifin is looking forward to showing their capabilities and versatility of the two-phase cooling technology with the aid of the ICS.

References

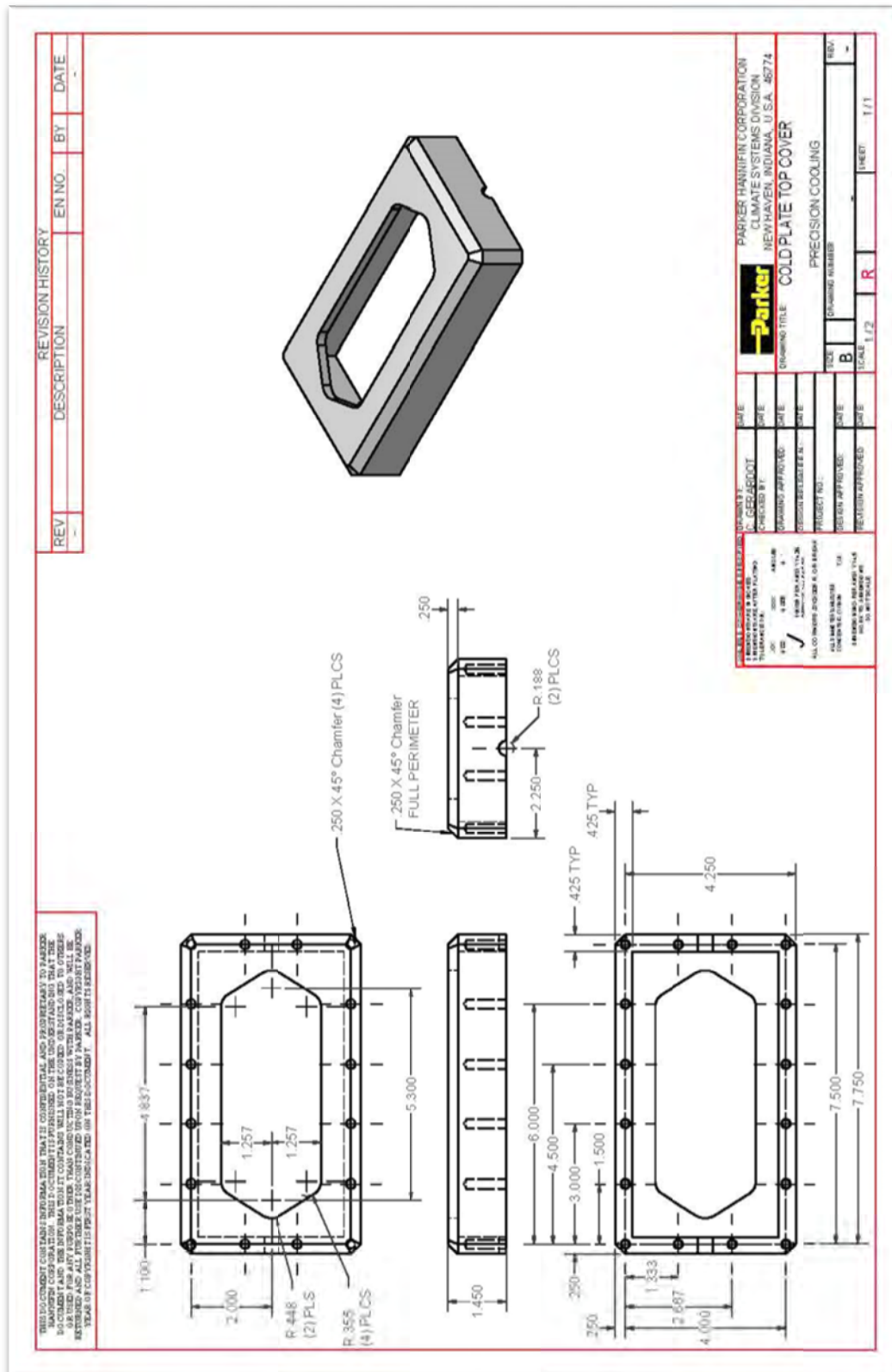
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Appendices

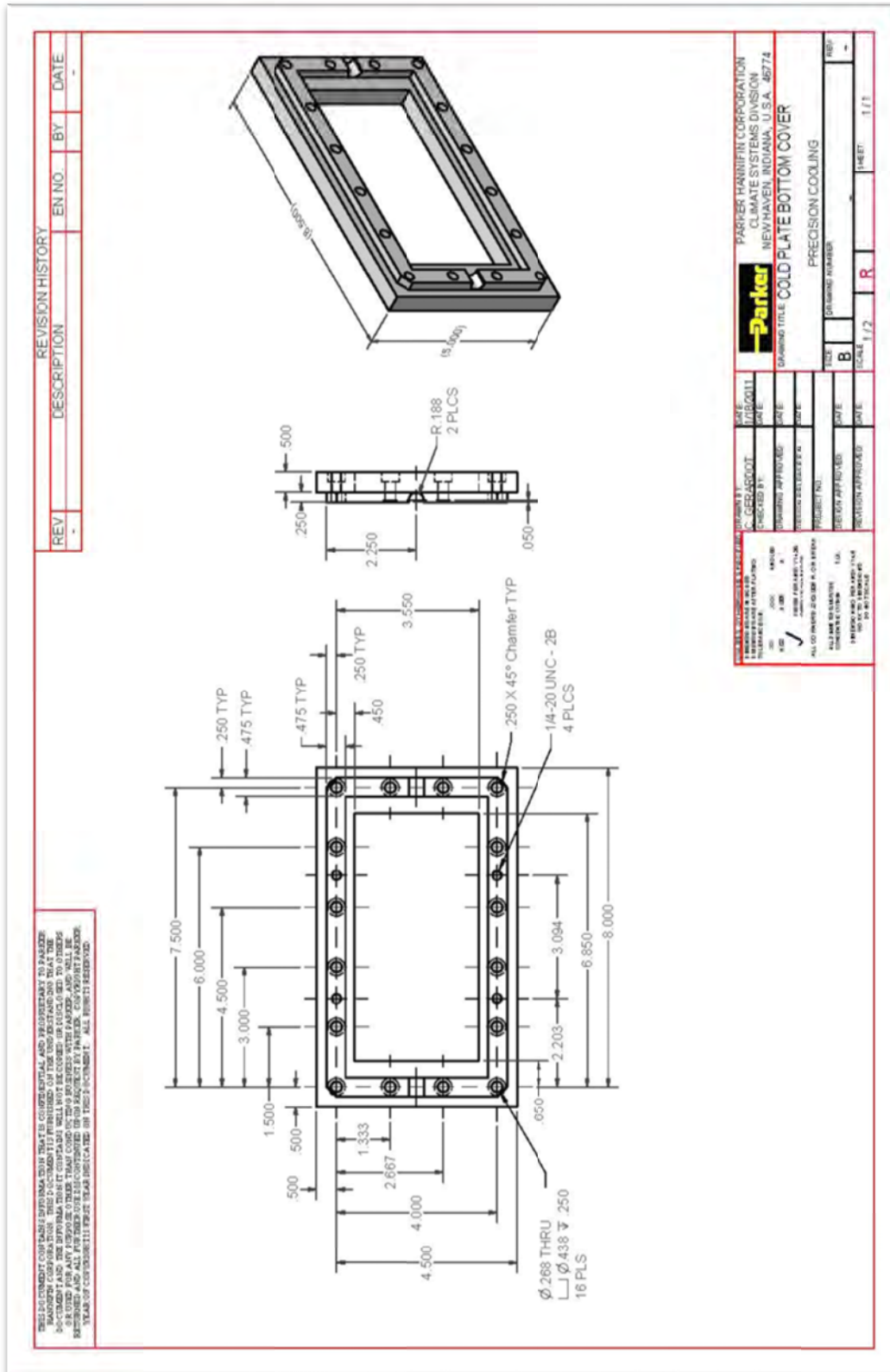
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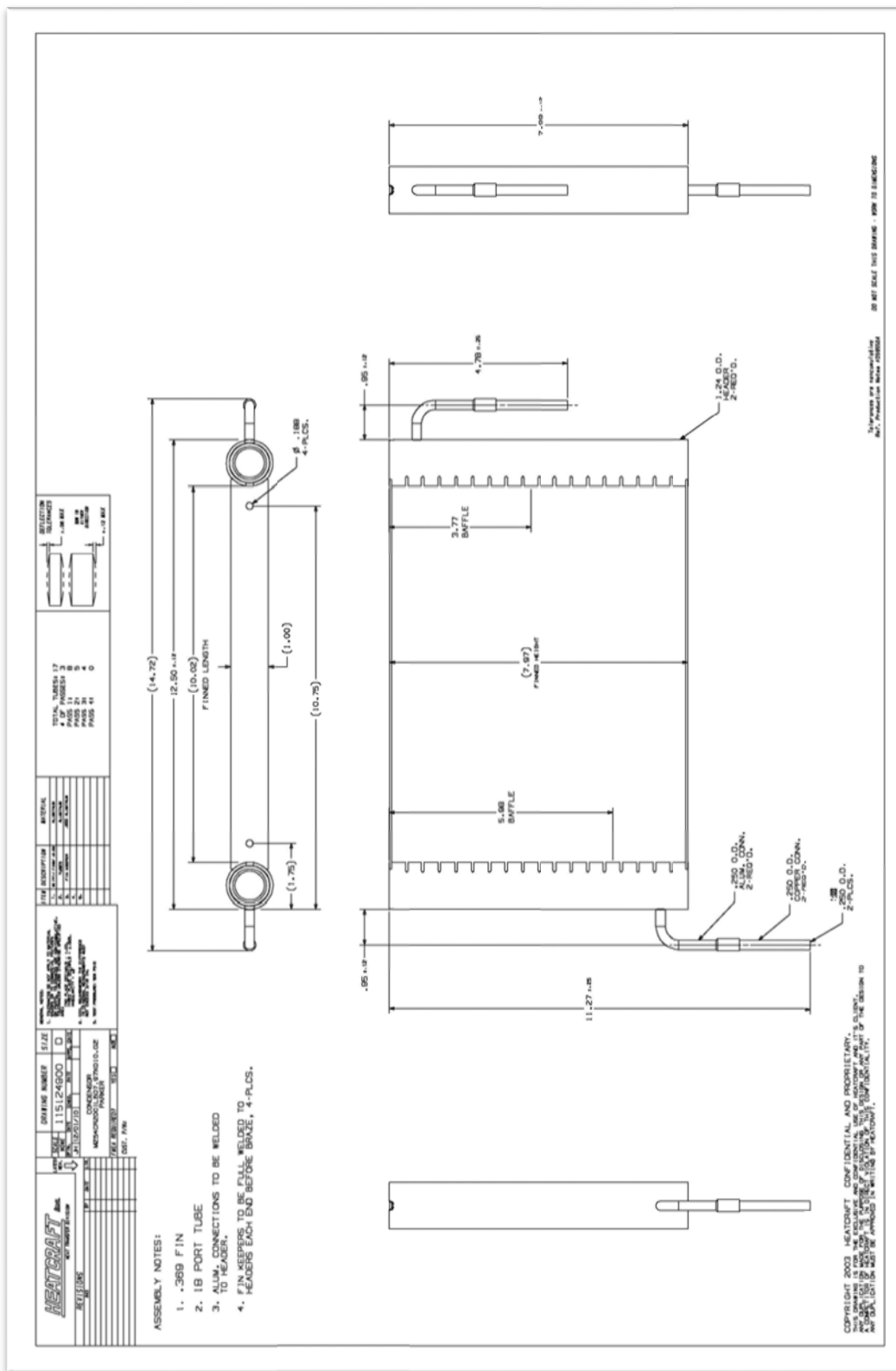
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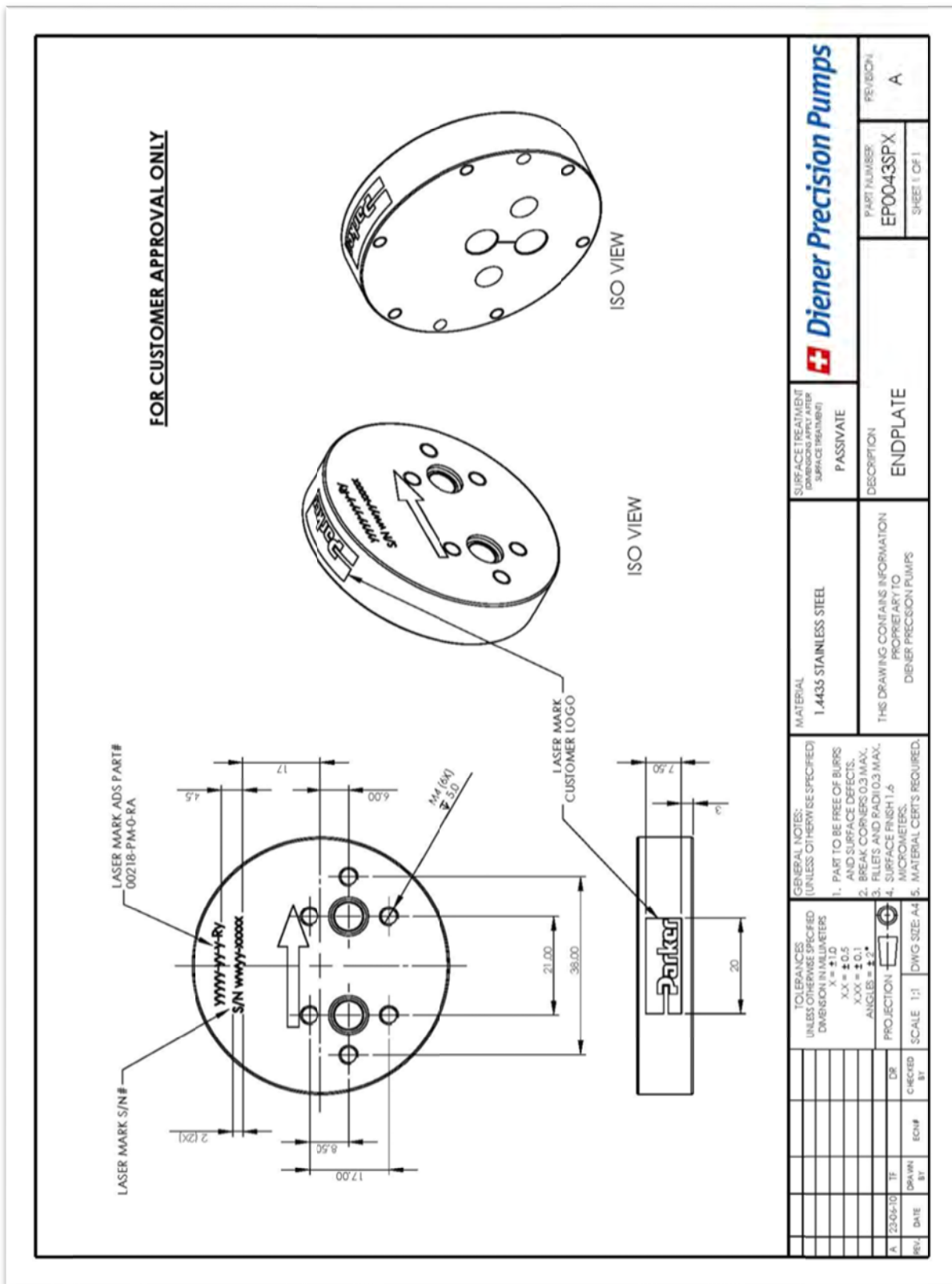
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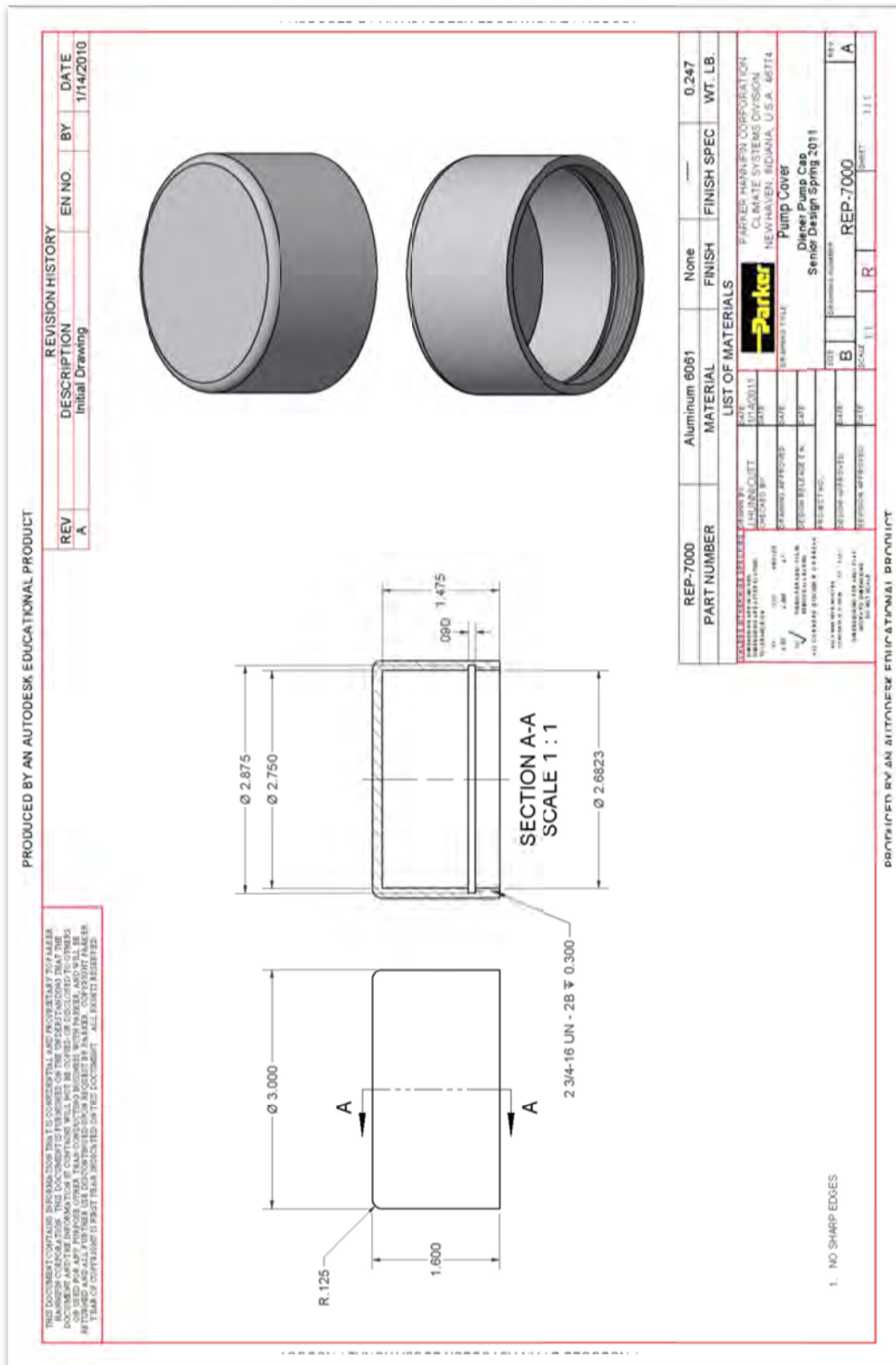
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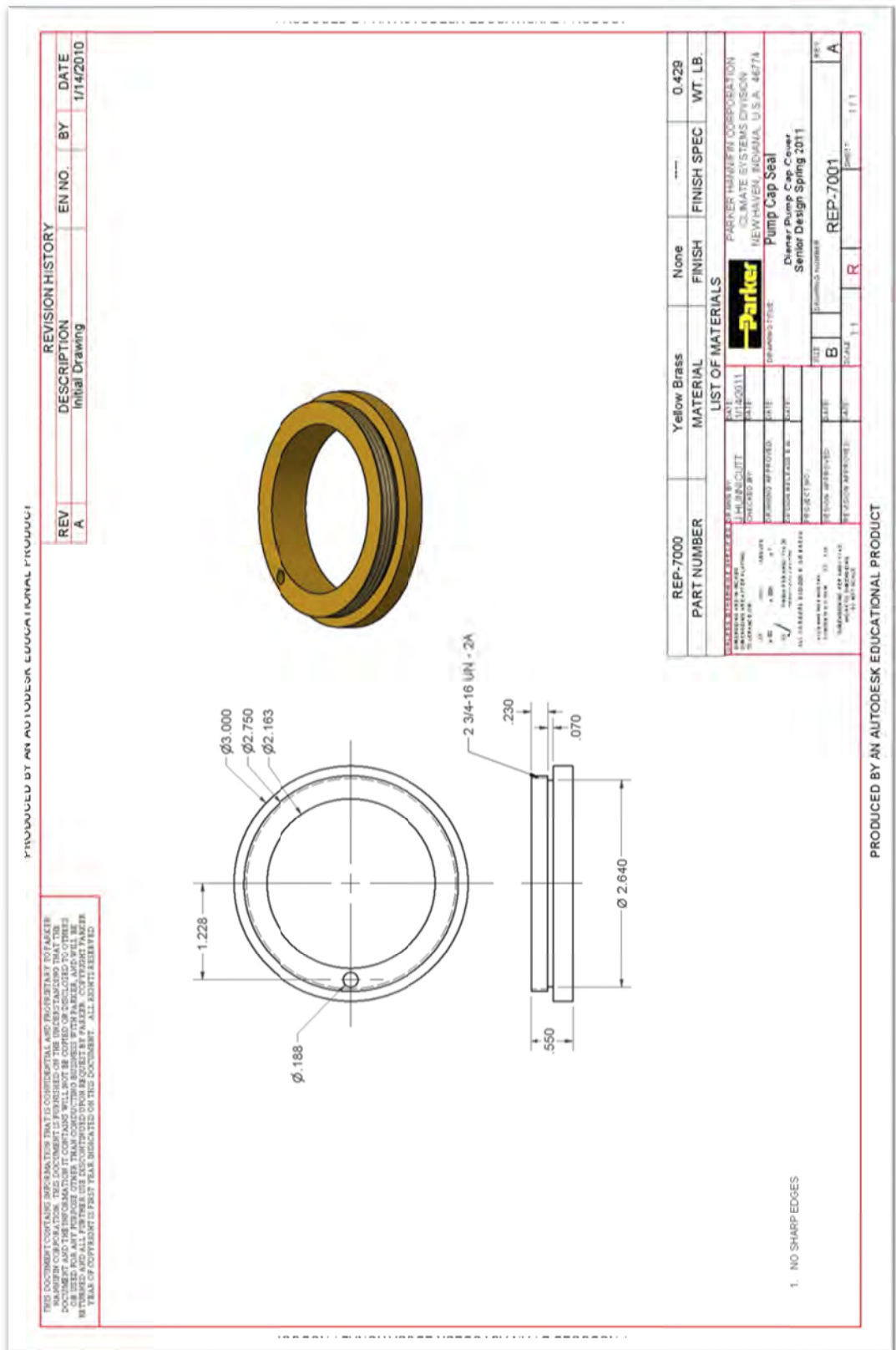
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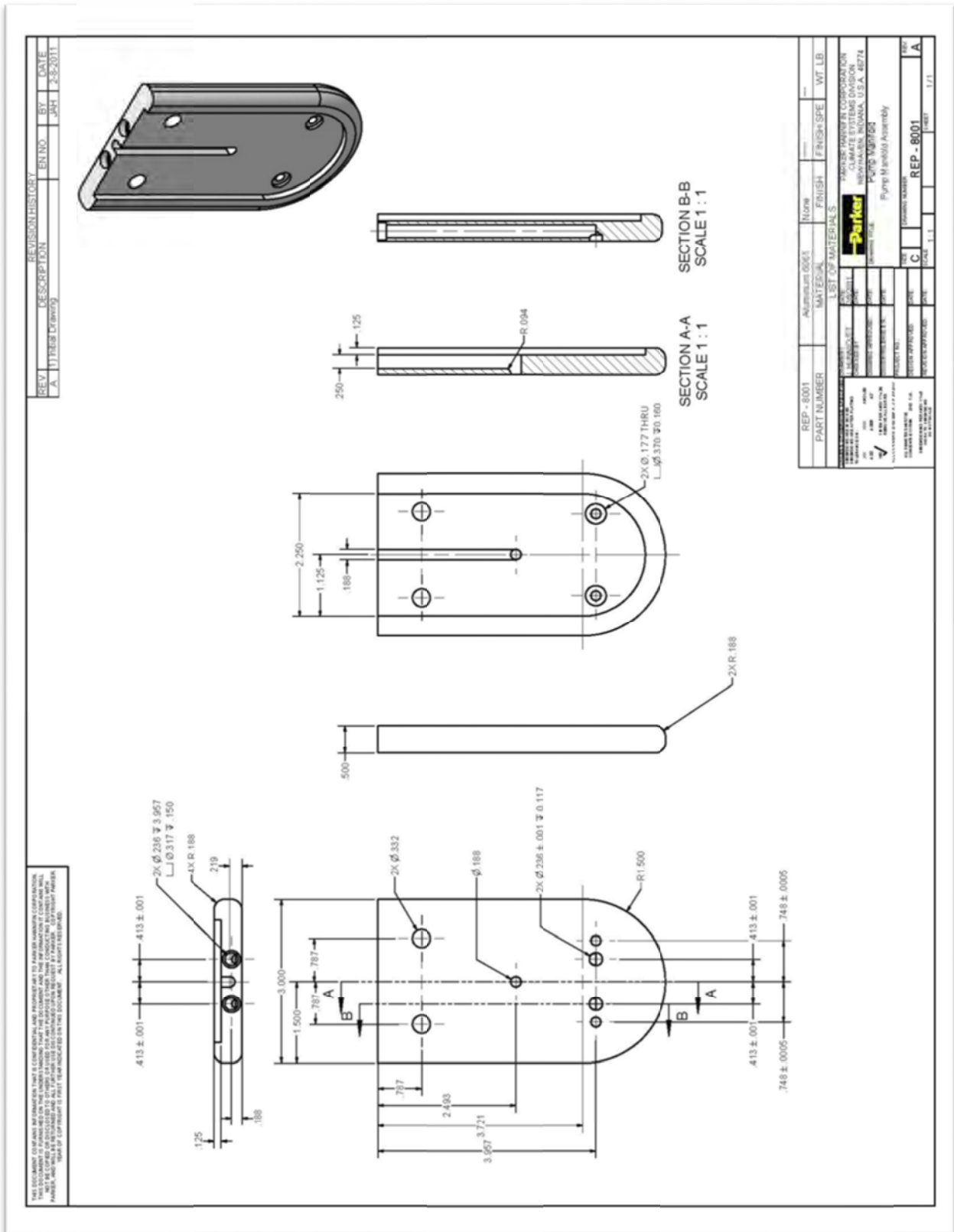
A-6: PUMP COVER



A-7: PUMP SEAL



A-8: PUMP MANIFOLD



A-9: PUMP MANIFOLD COVER PLATE

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A-10: HEATER BRACKETS

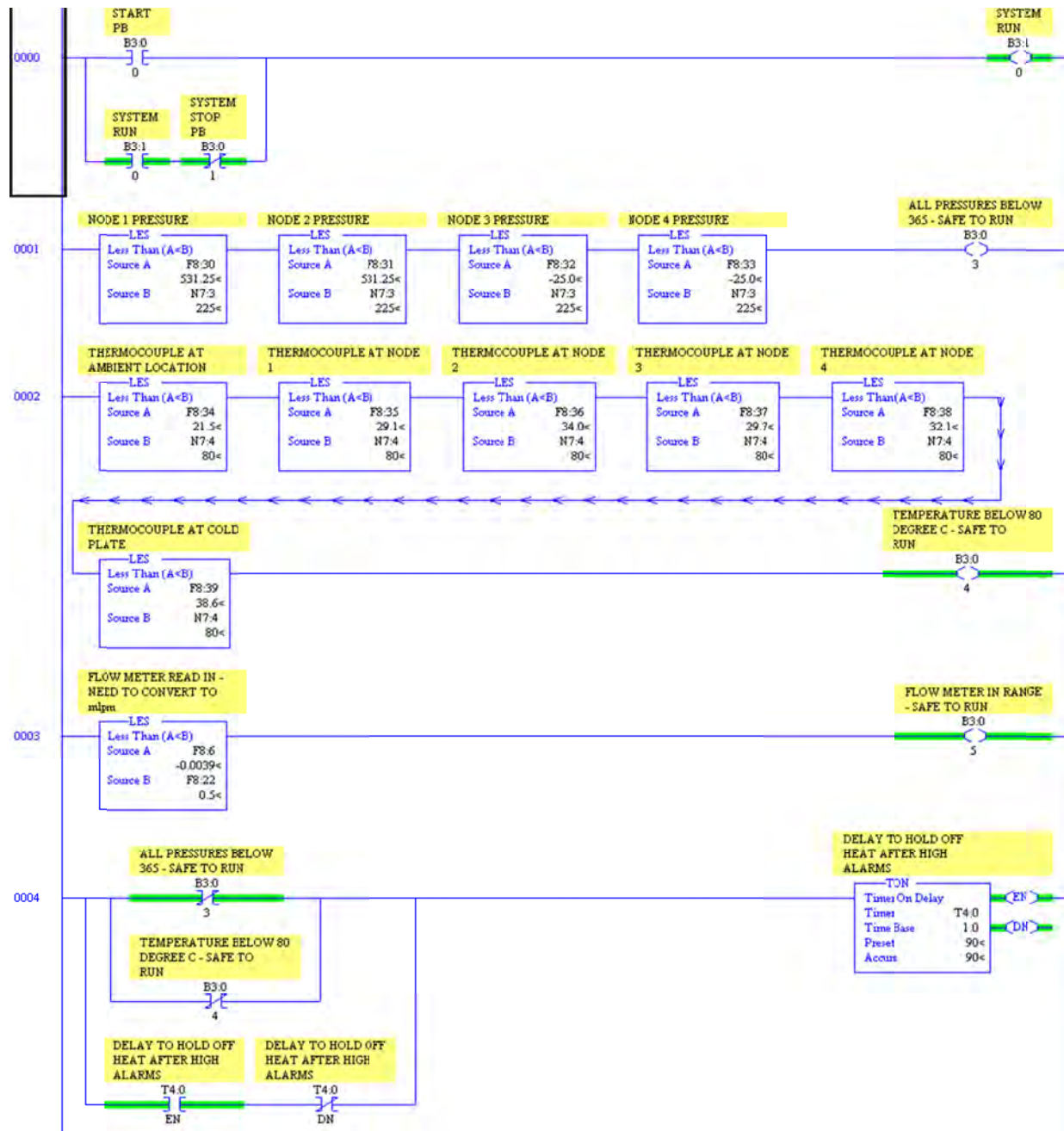
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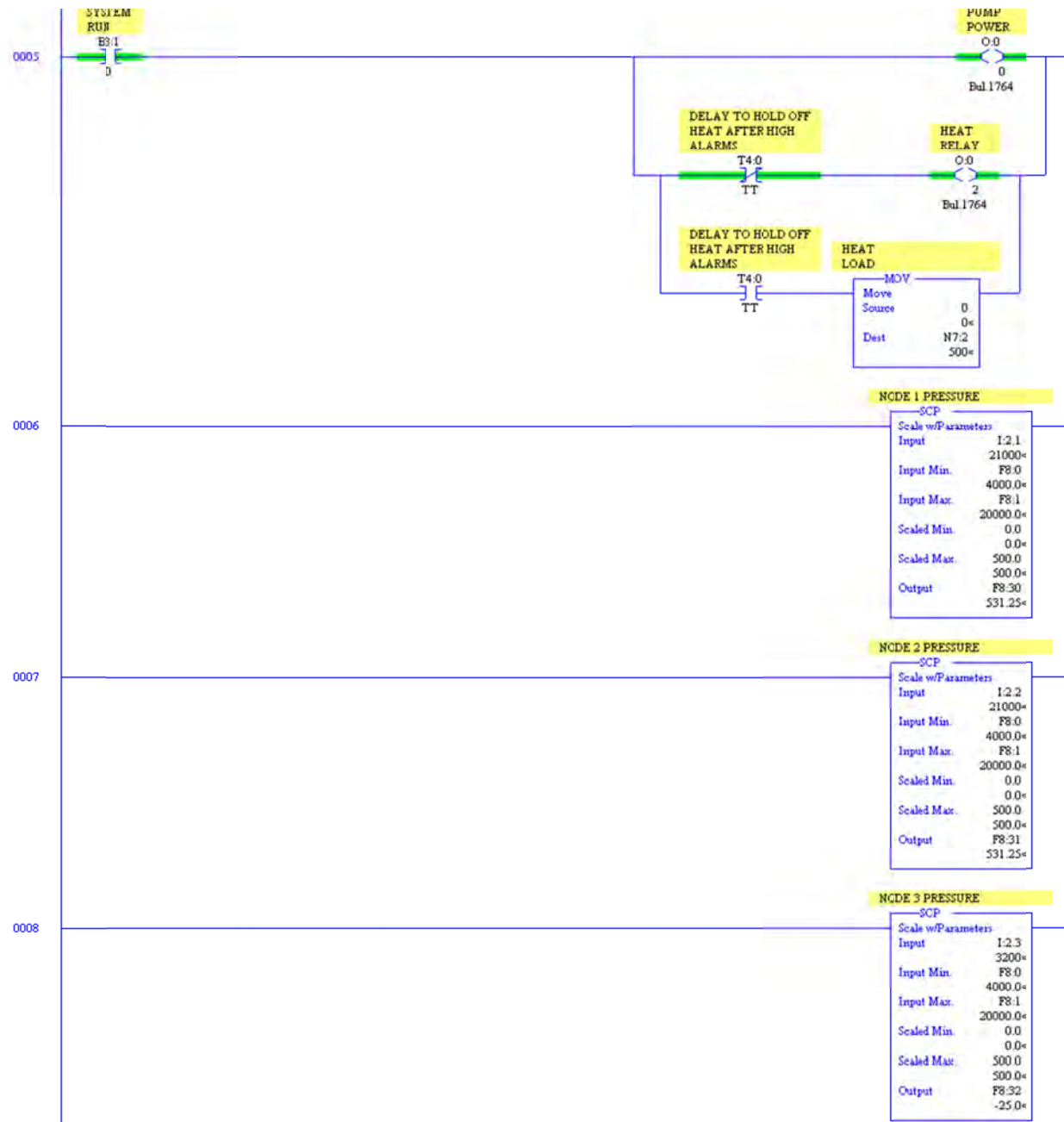
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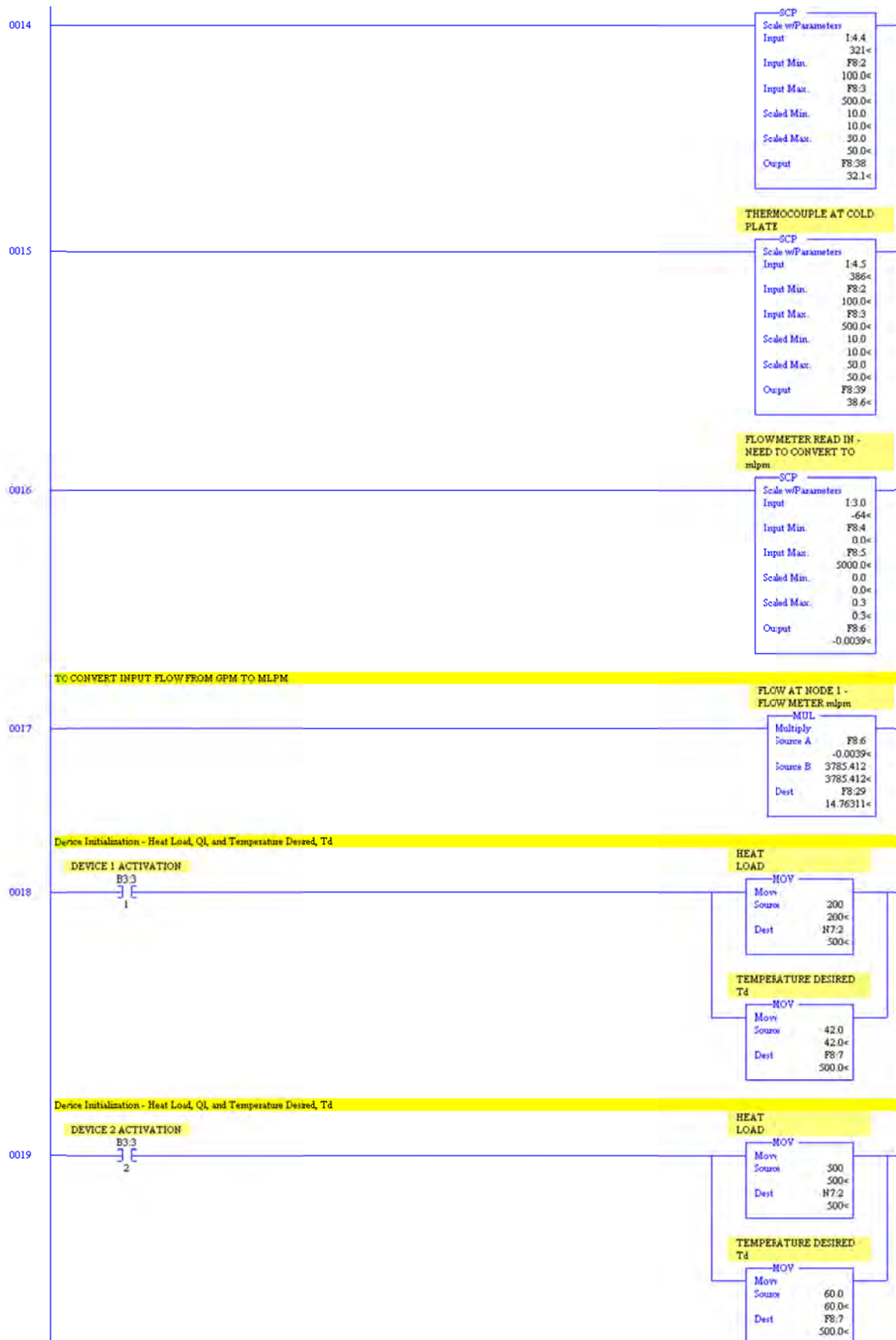
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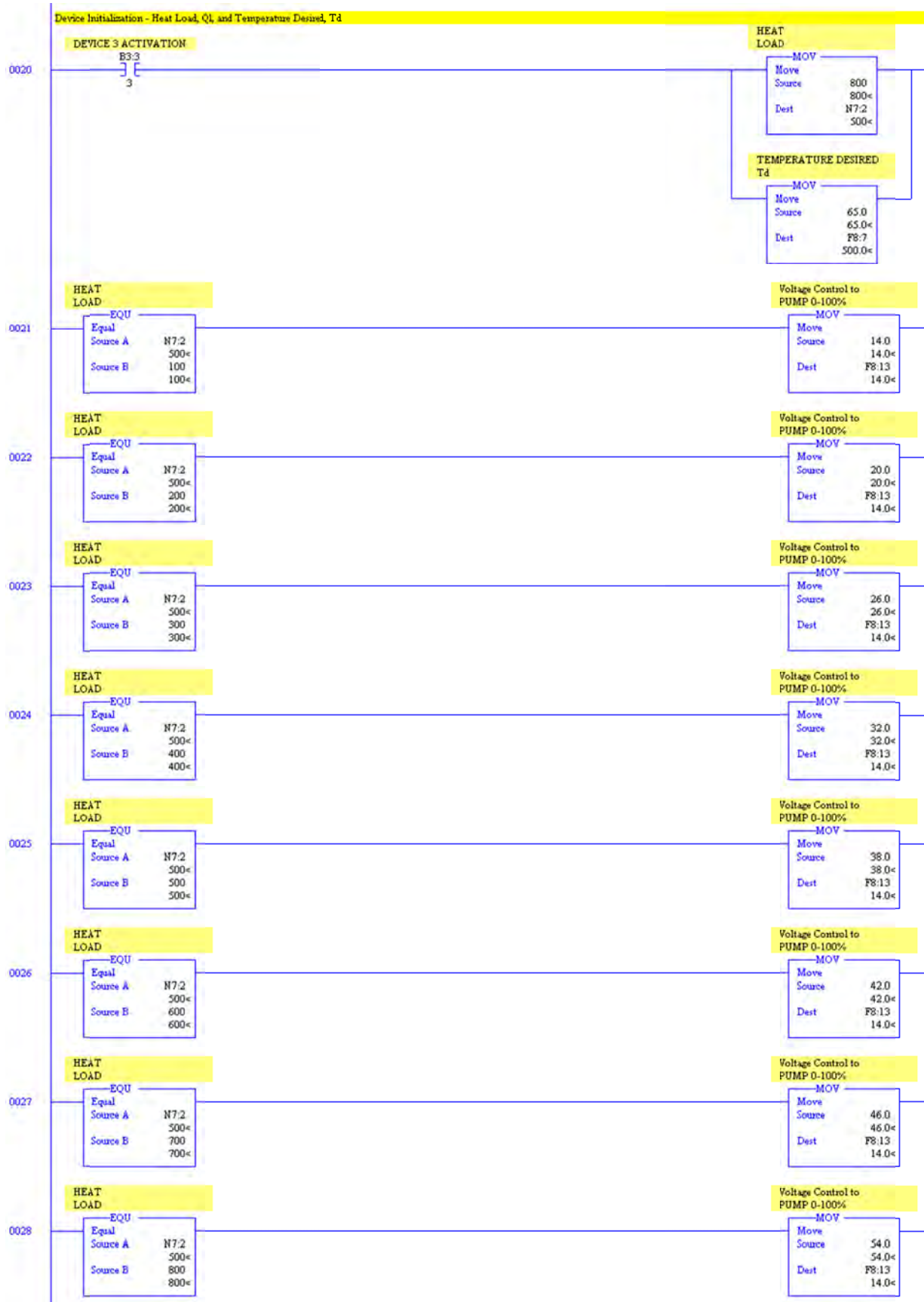
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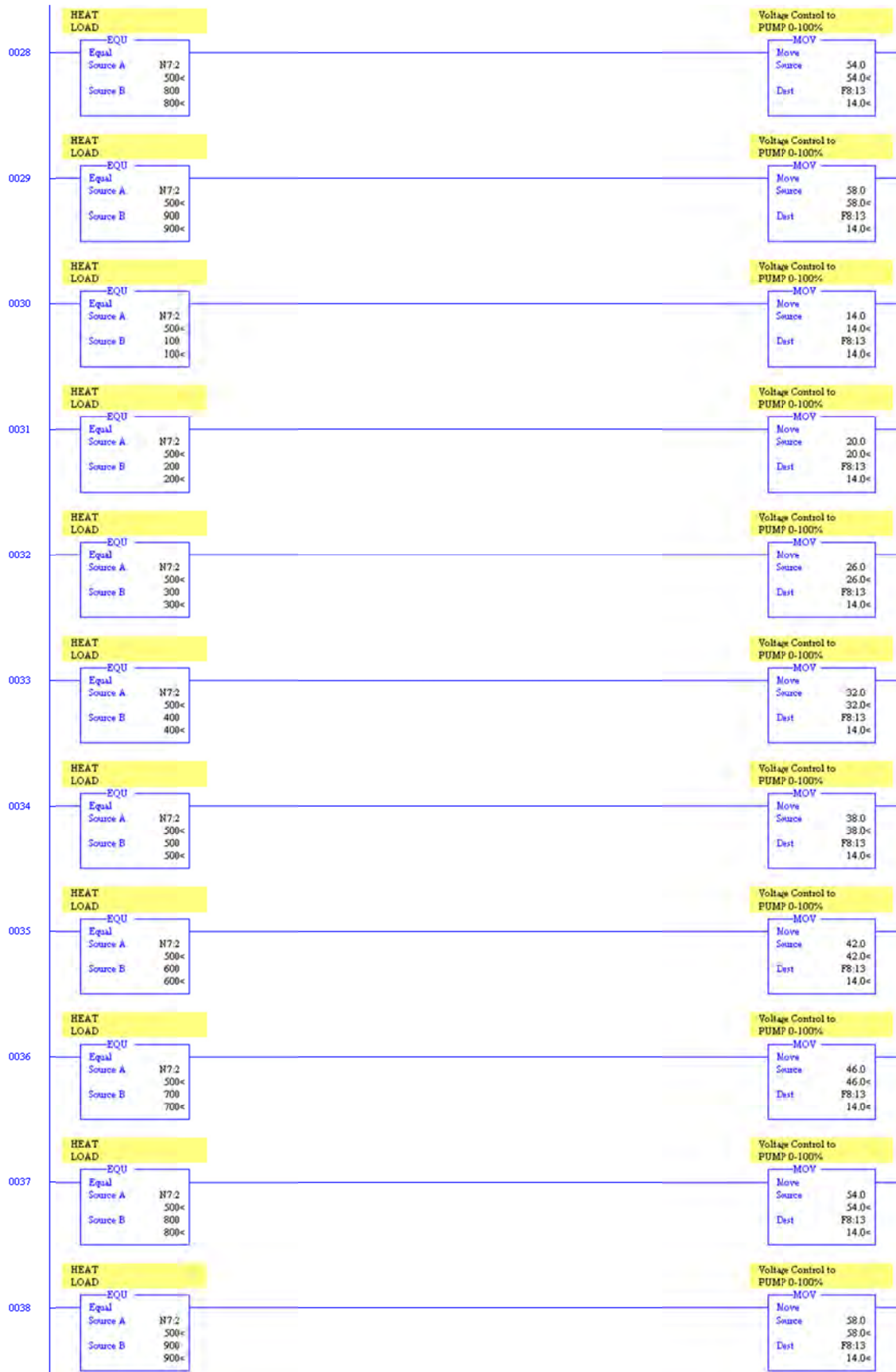
APPENDIX B: RS LOGIX 500 PROGRAMMING

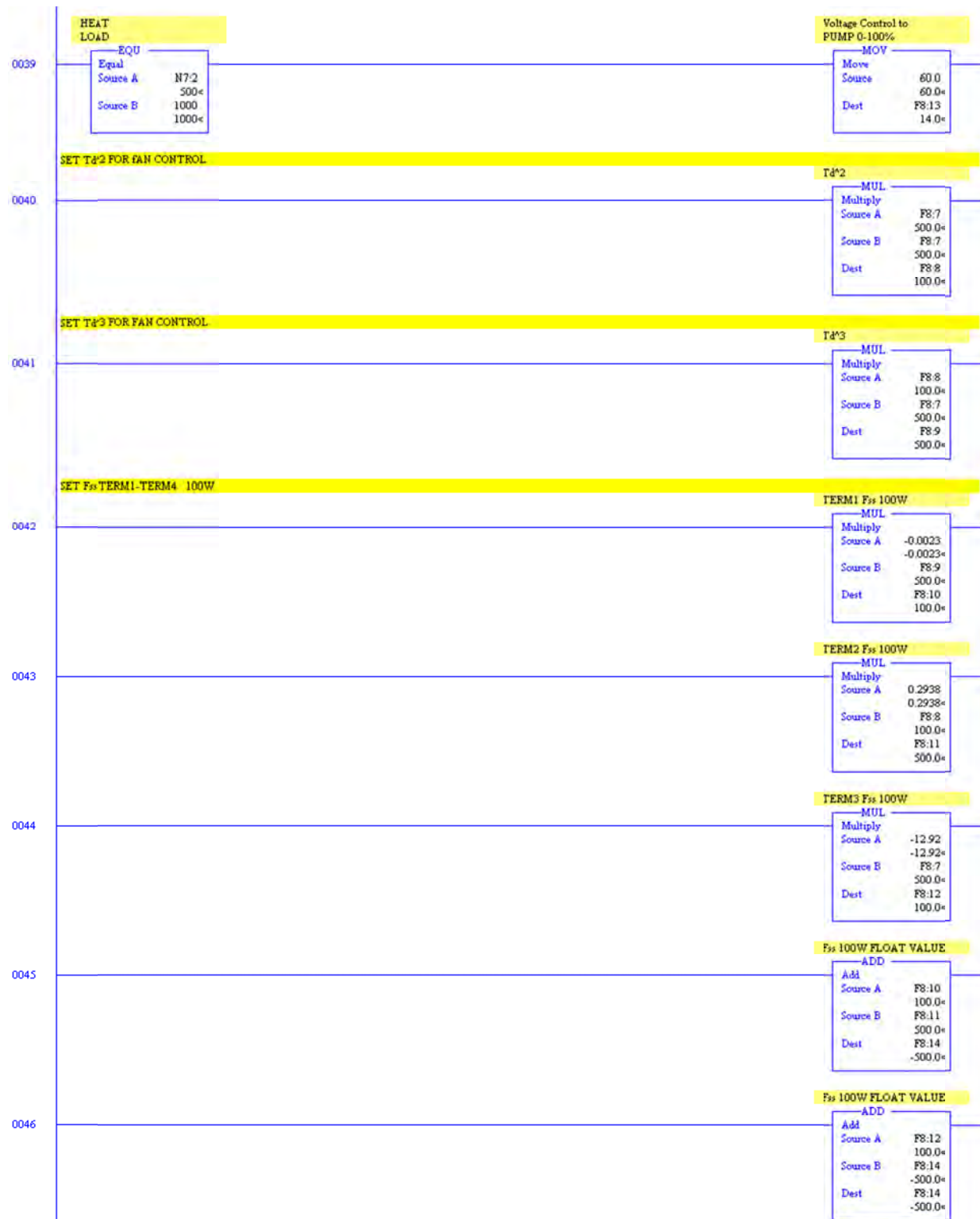












0047	<div>F32 100W FLOAT VALUE</div> <div>ADD</div> <table><tr><td>Add</td><td></td></tr><tr><td>Source A</td><td>195.72</td></tr><tr><td></td><td>195.72e</td></tr><tr><td>Source B</td><td>F8:14</td></tr><tr><td></td><td>-500.0e</td></tr><tr><td>Dest</td><td>F8:14</td></tr><tr><td></td><td>-500.0e</td></tr></table>	Add		Source A	195.72		195.72e	Source B	F8:14		-500.0e	Dest	F8:14		-500.0e
Add															
Source A	195.72														
	195.72e														
Source B	F8:14														
	-500.0e														
Dest	F8:14														
	-500.0e														
0048	<div>F32 100W</div> <div>MOV</div> <table><tr><td>Move</td><td></td></tr><tr><td>Source</td><td>F8:14</td></tr><tr><td></td><td>-500.0e</td></tr><tr><td>Dest</td><td>F8:90</td></tr><tr><td></td><td>0.0e</td></tr></table>	Move		Source	F8:14		-500.0e	Dest	F8:90		0.0e				
Move															
Source	F8:14														
	-500.0e														
Dest	F8:90														
	0.0e														
SET F32 TERM1-TERM4 200W															
0049	<div>TERM1 F32 200W</div> <div>MUL</div> <table><tr><td>Multiply</td><td></td></tr><tr><td>Source A</td><td>-0.0016</td></tr><tr><td></td><td>-0.0016e</td></tr><tr><td>Source B</td><td>F8:9</td></tr><tr><td></td><td>500.0e</td></tr><tr><td>Dest</td><td>F8:15</td></tr><tr><td></td><td>500.0e</td></tr></table>	Multiply		Source A	-0.0016		-0.0016e	Source B	F8:9		500.0e	Dest	F8:15		500.0e
Multiply															
Source A	-0.0016														
	-0.0016e														
Source B	F8:9														
	500.0e														
Dest	F8:15														
	500.0e														
0050	<div>TERM2 F32 200W</div> <div>MUL</div> <table><tr><td>Multiply</td><td></td></tr><tr><td>Source A</td><td>0.2425</td></tr><tr><td></td><td>0.2425e</td></tr><tr><td>Source B</td><td>F8:8</td></tr><tr><td></td><td>100.0e</td></tr><tr><td>Dest</td><td>F8:16</td></tr><tr><td></td><td>100.0e</td></tr></table>	Multiply		Source A	0.2425		0.2425e	Source B	F8:8		100.0e	Dest	F8:16		100.0e
Multiply															
Source A	0.2425														
	0.2425e														
Source B	F8:8														
	100.0e														
Dest	F8:16														
	100.0e														
0051	<div>TERM3 F32 200W</div> <div>MUL</div> <table><tr><td>Multiply</td><td></td></tr><tr><td>Source A</td><td>-12.754</td></tr><tr><td></td><td>-12.754e</td></tr><tr><td>Source B</td><td>F8:7</td></tr><tr><td></td><td>500.0e</td></tr><tr><td>Dest</td><td>F8:17</td></tr><tr><td></td><td>500.0e</td></tr></table>	Multiply		Source A	-12.754		-12.754e	Source B	F8:7		500.0e	Dest	F8:17		500.0e
Multiply															
Source A	-12.754														
	-12.754e														
Source B	F8:7														
	500.0e														
Dest	F8:17														
	500.0e														
0052	<div>F32 200W FLOAT VALUE</div> <div>ADD</div> <table><tr><td>Add</td><td></td></tr><tr><td>Source A</td><td>F8:15</td></tr><tr><td></td><td>500.0e</td></tr><tr><td>Source B</td><td>F8:16</td></tr><tr><td></td><td>100.0e</td></tr><tr><td>Dest</td><td>F8:18</td></tr><tr><td></td><td>100.0e</td></tr></table>	Add		Source A	F8:15		500.0e	Source B	F8:16		100.0e	Dest	F8:18		100.0e
Add															
Source A	F8:15														
	500.0e														
Source B	F8:16														
	100.0e														
Dest	F8:18														
	100.0e														
0053	<div>F32 200W FLOAT VALUE</div> <div>ADD</div> <table><tr><td>Add</td><td></td></tr><tr><td>Source A</td><td>F8:17</td></tr><tr><td></td><td>500.0e</td></tr><tr><td>Source B</td><td>F8:18</td></tr><tr><td></td><td>100.0e</td></tr><tr><td>Dest</td><td>F8:18</td></tr><tr><td></td><td>100.0e</td></tr></table>	Add		Source A	F8:17		500.0e	Source B	F8:18		100.0e	Dest	F8:18		100.0e
Add															
Source A	F8:17														
	500.0e														
Source B	F8:18														
	100.0e														
Dest	F8:18														
	100.0e														
0054	<div>F32 200W FLOAT VALUE</div> <div>ADD</div> <table><tr><td>Add</td><td></td></tr><tr><td>Source A</td><td>227.83</td></tr><tr><td></td><td>227.83e</td></tr><tr><td>Source B</td><td>F8:18</td></tr><tr><td></td><td>100.0e</td></tr><tr><td>Dest</td><td>F8:18</td></tr><tr><td></td><td>100.0e</td></tr></table>	Add		Source A	227.83		227.83e	Source B	F8:18		100.0e	Dest	F8:18		100.0e
Add															
Source A	227.83														
	227.83e														
Source B	F8:18														
	100.0e														
Dest	F8:18														
	100.0e														
0055	<div>F32 200W</div> <div>MOV</div> <table><tr><td>Move</td><td></td></tr><tr><td>Source</td><td>F8:18</td></tr><tr><td></td><td>100.0e</td></tr><tr><td>Dest</td><td>F8:91</td></tr><tr><td></td><td>0.0e</td></tr></table>	Move		Source	F8:18		100.0e	Dest	F8:91		0.0e				
Move															
Source	F8:18														
	100.0e														
Dest	F8:91														
	0.0e														

	SET F ₃₀ TERM1-TERM4 300W	
0056		<div> <div>TERM1 F₃₀ 300W</div> <div> <div>MUL</div> <div> Multiply Source A -0.0012 Source B -0.0012+ F8:9 500.0+ Dest F8:19 500.0+ </div> </div> </div>
0057		<div> <div>TERM2 F₃₀ 300W</div> <div> <div>MUL</div> <div> Multiply Source A 0.2007 Source B 0.2007+ F8:8 100.0+ Dest F8:20 3200.0+ </div> </div> </div>
0058		<div> <div>TERM3 F₃₀ 300W</div> <div> <div>MUL</div> <div> Multiply Source A -11.553 Source B -11.553+ F8:7 500.0+ Dest F8:21 21000.0+ </div> </div> </div>
0059		<div> <div>F₃₀ 300W FLOAT VALUE</div> <div> <div>ADD</div> <div> Add Source A F8:19 500.0+ Source B F8:20 3200.0+ Dest F8:23 0.0+ </div> </div> </div>
0060		<div> <div>F₃₀ 300W FLOAT VALUE</div> <div> <div>ADD</div> <div> Add Source A F8:21 21000.0+ Source B F8:23 0.0+ Dest F8:23 0.0+ </div> </div> </div>
0061		<div> <div>F₃₀ 300W FLOAT VALUE</div> <div> <div>ADD</div> <div> Add Source A 227.61 Source B 227.61+ F8:23 0.0+ Dest F8:23 0.0+ </div> </div> </div>
0062		<div> <div>F₃₀ 300W</div> <div> <div>MOV</div> <div> Move Source F8:23 0.0+ Dest F8:92 0.0+ </div> </div> </div>
	SET F ₃₀ TERM1-TERM4 400W	
0063		<div> <div>TERM1 F₃₀ 400W</div> <div> <div>MUL</div> <div> Multiply Source A -0.002 Source B -0.002+ F8:9 500.0+ Dest F8:24 0.0+ </div> </div> </div>

0064		<div>TERM2 F₈ 400W</div> <div>MUL</div> <div>Multiply</div> <div>Source A 0.3534</div> <div>Source B F8.8</div> <div>Dest F8.25</div> <div>81.60341e</div>
0065		<div>TERM3 F₈ 400W</div> <div>MUL</div> <div>Multiply</div> <div>Source A -20.939</div> <div>Source B F8.7</div> <div>Dest F8.26</div> <div>-20.939e</div> <div>500.0e</div> <div>0.0e</div>
0066		<div>F₈ 400W FLOAT VALUE</div> <div>ADD</div> <div>Add</div> <div>Source A F8.24</div> <div>Source B F8.25</div> <div>Dest F8.27</div> <div>0.0e</div> <div>81.60341e</div> <div>5000.0e</div>
0067		<div>F₈ 400W FLOAT VALUE</div> <div>ADD</div> <div>Add</div> <div>Source A F8.26</div> <div>Source B F8.27</div> <div>Dest F8.27</div> <div>0.0e</div> <div>5000.0e</div> <div>5000.0e</div>
0068		<div>F₈ 400W FLOAT VALUE</div> <div>ADD</div> <div>Add</div> <div>Source A 418.96</div> <div>Source B F8.27</div> <div>Dest F8.27</div> <div>418.96e</div> <div>5000.0e</div> <div>5000.0e</div>
0069		<div>F₈ 400W</div> <div>MOV</div> <div>Move</div> <div>Source F8.27</div> <div>Dest F8.93</div> <div>5000.0e</div> <div>0.0e</div>
SET F ₈ TERM1-TERM4 500W		
0070		<div>TERM1 F₈ 500W</div> <div>MUL</div> <div>Multiply</div> <div>Source A -0.0006</div> <div>Source B F8.9</div> <div>Dest F8.28</div> <div>-0.0006e</div> <div>500.0e</div> <div>0.0e</div>
0071		<div>TERM2 F₈ 500W</div> <div>MUL</div> <div>Multiply</div> <div>Source A 0.1136</div> <div>Source B F8.8</div> <div>Dest F8.40</div> <div>0.1136e</div> <div>100.0e</div> <div>556.25e</div>
0072		<div>TERM3 F₈ 500W</div> <div>MUL</div> <div>Multiply</div> <div>Source A -7.7901</div> <div>Source B F8.7</div> <div>Dest F8.41</div> <div>-7.7901e</div> <div>500.0e</div> <div>23.58495e</div>

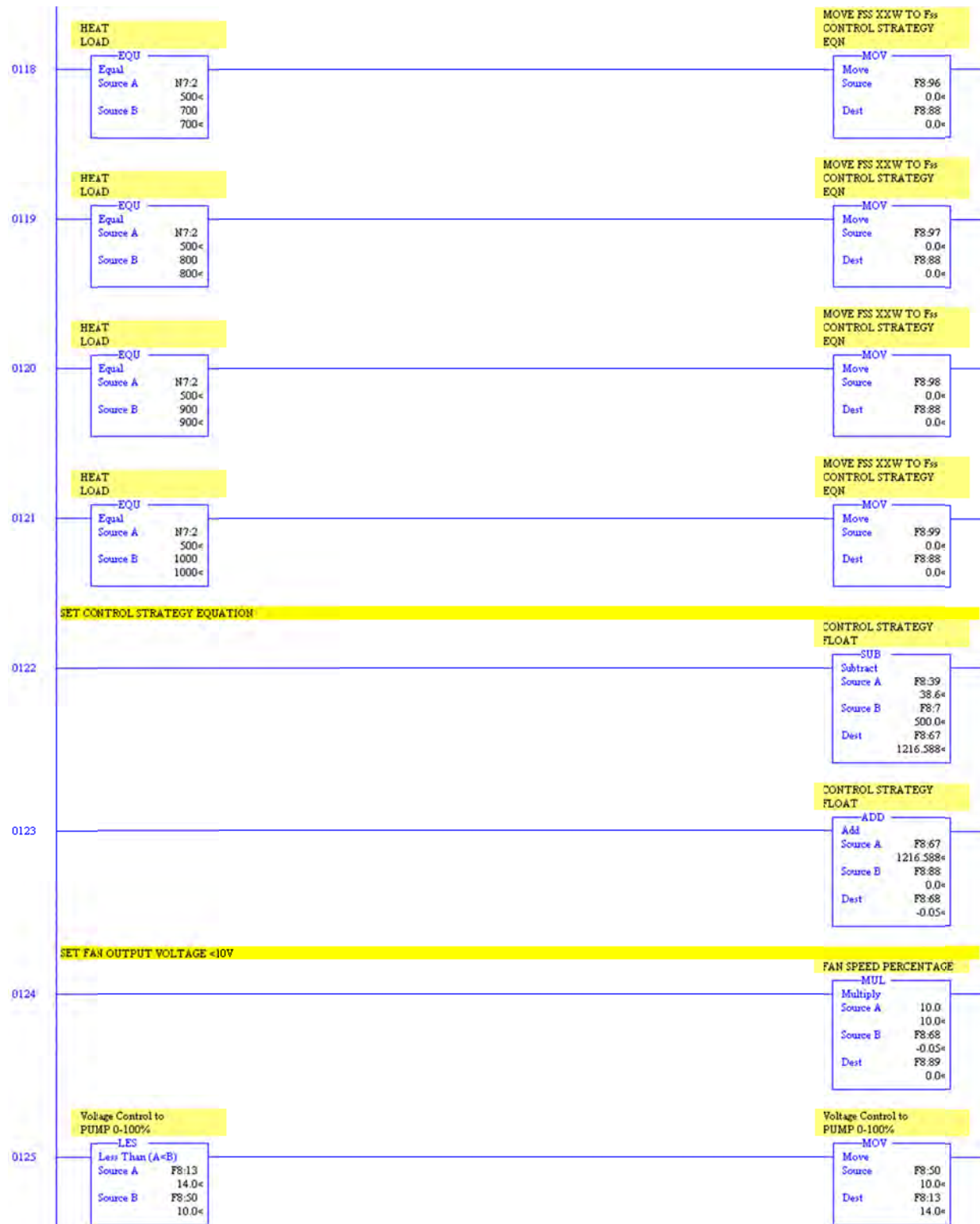
0073		<div>F8: 500W FLOAT VALUE</div> <div> <div>ADD</div> <div>Add</div> <div>Source A</div> <div>F8:28</div> <div>0.0*</div> <div>Source B</div> <div>F8:40</div> <div>556.25*</div> <div>Dest</div> <div>F8:42</div> <div>155.6607*</div> </div>
0074		<div>F8: 500W FLOAT VALUE</div> <div> <div>ADD</div> <div>Add</div> <div>Source A</div> <div>F8:41</div> <div>23.58495*</div> <div>Source B</div> <div>F8:42</div> <div>155.6607*</div> <div>Dest</div> <div>F8:42</div> <div>155.6607*</div> </div>
0075		<div>F8: 500W FLOAT VALUE</div> <div> <div>ADD</div> <div>Add</div> <div>Source A</div> <div>185.41</div> <div>185.41*</div> <div>Source B</div> <div>F8:42</div> <div>155.6607*</div> <div>Dest</div> <div>F8:42</div> <div>155.6607*</div> </div>
0076		<div>F8: 500W</div> <div> <div>MOV</div> <div>Move</div> <div>Source</div> <div>F8:42</div> <div>155.6607*</div> <div>Dest</div> <div>F8:94</div> <div>0.0*</div> </div>
SET F8, TERM1-TERM4 600W		
0077		<div>TERM1 F8: 600W</div> <div> <div>MUL</div> <div>Multiply</div> <div>Source A</div> <div>-0.0013</div> <div>-0.0013*</div> <div>Source B</div> <div>F8:9</div> <div>500.0*</div> <div>Dest</div> <div>F8:43</div> <div>0.0*</div> </div>
0078		<div>TERM2 F8: 600W</div> <div> <div>MUL</div> <div>Multiply</div> <div>Source A</div> <div>0.2703</div> <div>0.2703*</div> <div>Source B</div> <div>F8:8</div> <div>100.0*</div> <div>Dest</div> <div>F8:44</div> <div>0.0*</div> </div>
0079		<div>TERM3 F8: 600W</div> <div> <div>MUL</div> <div>Multiply</div> <div>Source A</div> <div>-18.64</div> <div>-18.64*</div> <div>Source B</div> <div>F8:7</div> <div>500.0*</div> <div>Dest</div> <div>F8:45</div> <div>0.0*</div> </div>
0080		<div>F8: 600W FLOAT VALUE</div> <div> <div>ADD</div> <div>Add</div> <div>Source A</div> <div>F8:43</div> <div>0.0*</div> <div>Source B</div> <div>F8:44</div> <div>0.0*</div> <div>Dest</div> <div>F8:46</div> <div>-106.6034*</div> </div>

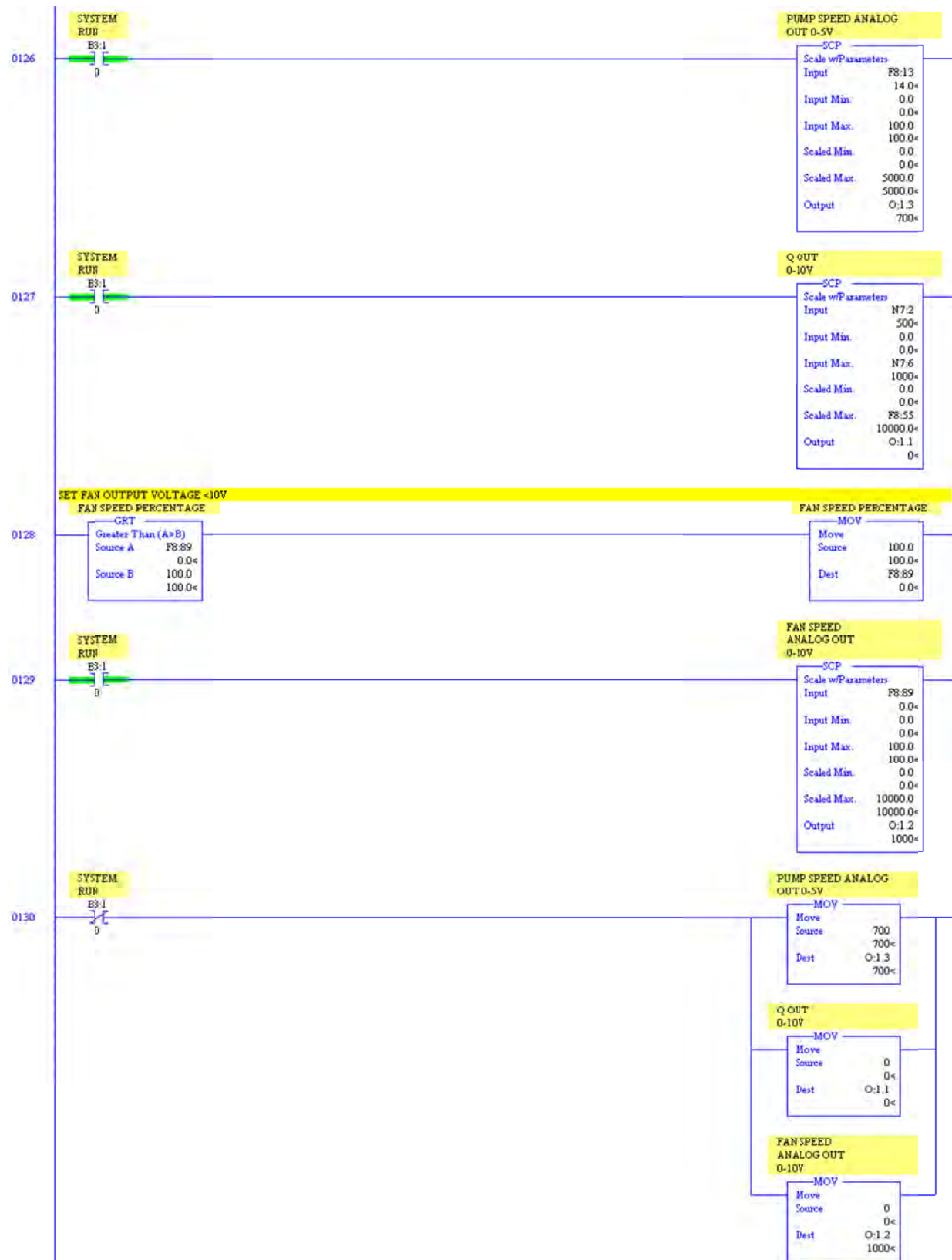
0082		<div>F32 600W FLOAT VALUE</div> <div> <div>ADD</div> <div>Add</div> <div>Source A434.14</div> <div>434.14*</div> <div>Source BF8.46</div> <div>-106.6034*</div> <div>DestF8.46</div> <div>-106.6034*</div> </div>
0083		<div>F32 600W</div> <div> <div>MOV</div> <div>Move</div> <div>SourceF8.46</div> <div>-106.6034*</div> <div>DestF8.95</div> <div>0.0*</div> </div>
SET F32 TERM1-TERM4 700W		
0084		<div>TERM1 F32 700W</div> <div> <div>MUL</div> <div>Multiply</div> <div>Source A-0.0005</div> <div>-0.0005*</div> <div>Source BF8.9</div> <div>500.0*</div> <div>DestF8.47</div> <div>4.4*</div> </div>
0085		<div>TERM2 F32 700W</div> <div> <div>MUL</div> <div>Multiply</div> <div>Source A0.1138</div> <div>0.1138*</div> <div>Source BF8.8</div> <div>100.0*</div> <div>DestF8.48</div> <div>0.0*</div> </div>
0086		<div>TERM3 F32 700W</div> <div> <div>MUL</div> <div>Multiply</div> <div>Source A-9.2583</div> <div>-9.2583*</div> <div>Source BF8.7</div> <div>500.0*</div> <div>DestF8.49</div> <div>0.0*</div> </div>
0087		<div>F32 700W FLOAT VALUE</div> <div> <div>ADD</div> <div>Add</div> <div>Source AF8.47</div> <div>4.4*</div> <div>Source BF8.48</div> <div>0.0*</div> <div>DestF8.51</div> <div>0.0*</div> </div>
0088		<div>F32 700W FLOAT VALUE</div> <div> <div>ADD</div> <div>Add</div> <div>Source AF8.49</div> <div>0.0*</div> <div>Source BF8.51</div> <div>0.0*</div> <div>DestF8.51</div> <div>0.0*</div> </div>
0089		<div>F32 700W FLOAT VALUE</div> <div> <div>ADD</div> <div>Add</div> <div>Source A256.68</div> <div>256.68*</div> <div>Source BF8.51</div> <div>0.0*</div> <div>DestF8.51</div> <div>0.0*</div> </div>

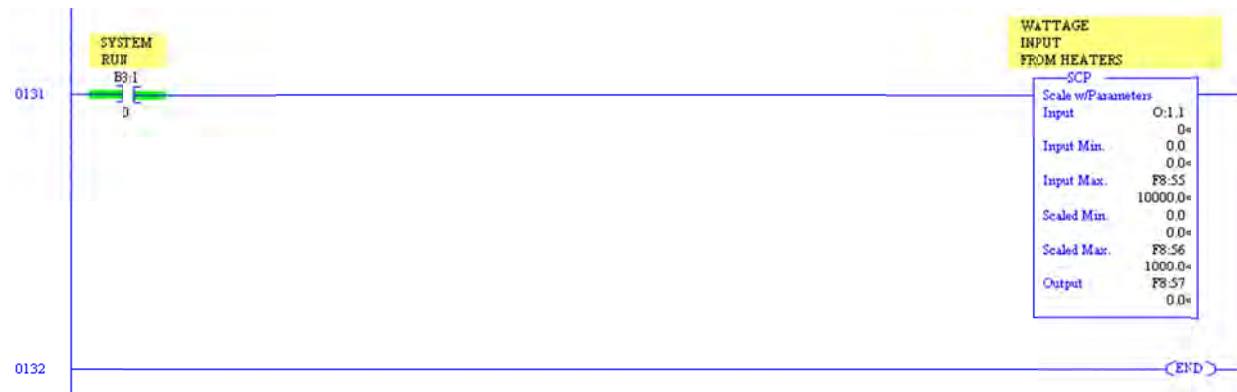
0090		F55 100W MOV Move Source F8:51 0.0e Dest F8:96 0.0e
		SET F55 TERM1-TERM4 800W
0091		TERM1 F55 800W MUL Multiply Source A 3E-005 3E-005e Source B F8:9 500.0e Dest F8:52 0.0e
0092		TERM2 F55 800W MUL Multiply Source A 0.221 0.221e Source B F8:8 100.0e Dest F8:53 0.0e
0093		TERM3 F55 800W MUL Multiply Source A -3.951 -3.951e Source B F8:7 500.0e Dest F8:54 0.0e
0094		F55 800W FLOAT VALUE ADD Add Source A F8:52 0.0e Source B F8:53 0.0e Dest F8:58 0.0e
0095		F55 800W FLOAT VALUE ADD Add Source A F8:54 0.0e Source B F8:58 0.0e Dest F8:58 0.0e
0096		F55 800W FLOAT VALUE ADD Add Source A 164.3 164.3e Source B F8:58 0.0e Dest F8:58 0.0e
0097		F55 800W MOV Move Source F8:58 0.0e Dest F8:97 0.0e
		SET F55 TERM1-TERM4 900W
0098		TERM1 F55 900W MUL Multiply Source A 0.0045 0.0045e Source B F8:9 500.0e Dest F8:59 0.0e
0099		TERM2 F55 900W MUL Multiply Source A -0.9584 -0.9584e Source B F8:8 100.0e Dest F8:60 0.0e

0100		<div> <div>TERMS F₉ 900W</div> <div> <div>MUL</div> <div> Multiply Source A 67.287 Source B F8.7 500.0+ Dest F8.61 0.0001634437+ </div> </div> </div>
0101		<div> <div>F₉ 900W FLOAT VALUE</div> <div> <div>ADD</div> <div> Add Source A F8.59 Source B F8.60 Dest F8.62 0.1988436+ </div> </div> </div>
0102		<div> <div>F₉ 900W FLOAT VALUE</div> <div> <div>ADD</div> <div> Add Source A F8.61 0.0001634437+ Source B F8.62 Dest F8.62 0.1988436+ </div> </div> </div>
0103		<div> <div>F₉ 900W FLOAT VALUE</div> <div> <div>ADD</div> <div> Add Source A -1546.6 Source B F8.62 Dest F8.62 0.1988436+ </div> </div> </div>
0104		<div> <div>F₉ 900W</div> <div> <div>MOV</div> <div> Move Source F8.62 Dest F8.98 0.0+ </div> </div> </div>
SET F ₉ TERM1-TERM4 1000W		
0105		<div> <div>TERM1 F₉ 1000W</div> <div> <div>MUL</div> <div> Multiply Source A 0.0083 Source B F8.9 500.0+ Dest F8.63 625.0+ </div> </div> </div>
0106		<div> <div>TERM2 F₉ 1000W</div> <div> <div>MUL</div> <div> Multiply Source A -1.8498 Source B F8.8 100.0+ Dest F8.64 -13.375+ </div> </div> </div>
0107		<div> <div>TERM3 F₉ 1000W</div> <div> <div>MUL</div> <div> Multiply Source A 135.93 Source B F8.7 500.0+ Dest F8.65 56.4375+ </div> </div> </div>
0108		<div> <div>F₉ 1000W FLOAT VALUE</div> <div> <div>ADD</div> <div> Add Source A F8.63 Source B F8.64 Dest F8.66 -69.8125+ </div> </div> </div>

0109		<div>FSS 1000W FLOAT VALUE</div> <div>ADD</div> <table><tr><td>Add</td><td></td></tr><tr><td>Source A</td><td>F8.65</td></tr><tr><td></td><td>56.4375*</td></tr><tr><td>Source B</td><td>F8.66</td></tr><tr><td></td><td>-69.8125*</td></tr><tr><td>Dest</td><td>F8.66</td></tr><tr><td></td><td>-69.8125*</td></tr></table>	Add		Source A	F8.65		56.4375*	Source B	F8.66		-69.8125*	Dest	F8.66		-69.8125*						
Add																						
Source A	F8.65																					
	56.4375*																					
Source B	F8.66																					
	-69.8125*																					
Dest	F8.66																					
	-69.8125*																					
0110		<div>FSS 1000W FLOAT VALUE</div> <div>ADD</div> <table><tr><td>Add</td><td></td></tr><tr><td>Source A</td><td>-3302.7</td></tr><tr><td></td><td>-3302.7*</td></tr><tr><td>Source B</td><td>F8.66</td></tr><tr><td></td><td>-69.8125*</td></tr><tr><td>Dest</td><td>F8.66</td></tr><tr><td></td><td>-69.8125*</td></tr></table>	Add		Source A	-3302.7		-3302.7*	Source B	F8.66		-69.8125*	Dest	F8.66		-69.8125*						
Add																						
Source A	-3302.7																					
	-3302.7*																					
Source B	F8.66																					
	-69.8125*																					
Dest	F8.66																					
	-69.8125*																					
0111		<div>FSS 1000W</div> <div>MOV</div> <table><tr><td>Move</td><td></td></tr><tr><td>Source</td><td>F8.66</td></tr><tr><td></td><td>-69.8125*</td></tr><tr><td>Dest</td><td>F8.99</td></tr><tr><td></td><td>0.0*</td></tr></table>	Move		Source	F8.66		-69.8125*	Dest	F8.99		0.0*										
Move																						
Source	F8.66																					
	-69.8125*																					
Dest	F8.99																					
	0.0*																					
0112	<div>HEAT LOAD</div> <div>EQU</div> <table><tr><td>Equal</td><td></td></tr><tr><td>Source A</td><td>N7.2</td></tr><tr><td></td><td>500<</td></tr><tr><td>Source B</td><td>100</td></tr><tr><td></td><td>100<</td></tr></table>	Equal		Source A	N7.2		500<	Source B	100		100<	<div>MOVE FSS XXW TO FSS CONTROL STRATEGY EQN</div> <div>MOV</div> <table><tr><td>Move</td><td></td></tr><tr><td>Source</td><td>F8.90</td></tr><tr><td></td><td>0.0*</td></tr><tr><td>Dest</td><td>F8.88</td></tr><tr><td></td><td>0.0*</td></tr></table>	Move		Source	F8.90		0.0*	Dest	F8.88		0.0*
Equal																						
Source A	N7.2																					
	500<																					
Source B	100																					
	100<																					
Move																						
Source	F8.90																					
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0116	<div>HEAT LOAD</div> <div>EQU</div> <table><tr><td>Equal</td><td></td></tr><tr><td>Source A</td><td>N7.2</td></tr><tr><td></td><td>500<</td></tr><tr><td>Source B</td><td>500</td></tr><tr><td></td><td>500<</td></tr></table>	Equal		Source A	N7.2		500<	Source B	500		500<	<div>MOVE FSS XXW TO FSS CONTROL STRATEGY EQN</div> <div>MOV</div> <table><tr><td>Move</td><td></td></tr><tr><td>Source</td><td>F9.94</td></tr><tr><td></td><td>0.0*</td></tr><tr><td>Dest</td><td>F8.88</td></tr><tr><td></td><td>0.0*</td></tr></table>	Move		Source	F9.94		0.0*	Dest	F8.88		0.0*
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Source B	600																					
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Move																						
Source	F8.95																					
	0.0*																					
Dest	F8.88																					
	0.0*																					







APPENDIX C: PUMP PROGRAMMING

C-1: MATLAB

```
for Q=100:1000
    for T=20:100
        T_FLUID=-(Q/1000*15-T);
        delta_h = -1.529647E-09*T_FLUID^6 + 3.970166E-07*T_FLUID^5 - 3.929848E-05*T_FLUID^4 +
            1.794693E-03*T_FLUID^3 - 4.042677E-02*T_FLUID^2 - 2.905297E-01*T_FLUID + 1.583218E02;
        m_dot(Q-99,T-19)=Q/1000/delta_h;

        density = -8E-09*T_FLUID^6 + 2E-06*T_FLUID^5 - 0.0002*T_FLUID^4 + 0.01*T_FLUID^3 -
            0.2329*T_FLUID^2 - 1.2427*T_FLUID + 1293.4 ;
        v_dot(Q-99,T-19)=m_dot(Q-99,T-19)/density*1e6*60;
    end
end
```

% The delta_h is basically a difference between the saturated enthalpy and the 70%
% quality enthalpy. The equations for that and the density were developed
% after we plotted a whole bunch of data points in Excel. The m_dot is the mass-flow
% rate. The v-dot is the volume flow rate.

% Basically (removing the unit-conversion factors), v_dot=m_dot/density, where density is a
% function of the temperature of the fluid shown in line 10. m_dot=Q/delta_h,
% where delta_h is a function of the temperature of the fluid in line 7.

% v_dot=Q/(delta_h*density).

% As you can see, both temperature and heat-input play a role in the pump speed

Note: The MATLAB code generates values for T from 20°C to 100°C and heat loads from 100W to 1000W. The tables in the control section only show the values for 35°C to 100°C in increments of 5°C and heat loads from 100W to 1000W in increments of 100W. Equations came from DuPont R-134a thermodynamic SI tables [2]

C-2: EES PROGRAM

```
"Heat In"
Q_dot=.1
"Critical Temperature"
T_cp=45
"Cold Plate Dimensions"
A_cp=0.0087870792
"Heat Transfer Equations"
R_cp=50
"R134A Flow Rate"
m_dot_R134A=Q_dot/(h_2-h_1)
"State 1"
x_1=0
T_1=-(Q_dot*R_cp-T_cp)
P_1=Pressure(R134A,T=T_1,x=x_1)
h_1=Enthalpy(R134A,T=T_1,x=x_1)
s_1=Entropy(R134A,T=T_1,x=x_1)
rho_1=Density(R134A,T=T_1,x=x_1)
"State 2"
x_2=0.43
T_2=T_1
P_2=Pressure(R134A,T=T_2,x=x_2)
h_2=Enthalpy(R134A,T=T_2,x=x_2)
s_2=Entropy(R134A,T=T_2,x=x_2)
"State 3"
x_3=x_1
T_3=T_1
P_3=P_1-80
h_3=h_1
s_3=s_1
"Air"
T_5=22
P_5=101
h_5=Enthalpy(Air,T=T_5)
"State 6"
T_6=25
P_6=P_5
h_6=Enthalpy(Air,T=T_6)
"Fan Flow Rate"
m_dot_fan=m_dot_R134A*(h_1-h_2)/(h_5-h_6)
"Flow Rate to ml/min"
pump=m_dot_R134A/rho_1/1e-6*60
```

*Note – The Heat Input and Critical Temperature may be varied as necessary to find the corresponding volumetric pump flow rate. The actual flow rate sent to the pump is sent in the form of a voltage signal. 5 [V] corresponds to 1000 [mL/minute]. The relationship is linear down to 0 [V], which corresponds to 0 [mL/minute].

APPENDIX D: MATLAB CODE FOR PLANT – SIMULINK MODEL

```
%% parameters
%%%
Kp=1;

%%
q1=62.225; %length of piping 1 in inches
L1=q1*0.0254; %length of piping 1 in meters
a1=0.029559; %cross sectional area 1 in in^2
A1=a1*0.0254^2; %cross sectional area 1 in m^2

q2=8; %length of piping 2 in inches
L2=q2*0.0254; %length of piping 2 in meters
a2=0.073062; %cross sectional area 2 in in^2
A2=a2*0.0254^2; %cross sectional area 2 in m^2

q3=11.258; %length of piping 3 in inches
L3=q3*0.0254; %length of piping 3 in meters
u3=0.029; %diameter of piping 3 in inches
d3=u3*0.0254; %diameter of piping 3 in meters
A3=pi*d3^2/4; %cross sectional area of piping 3 in m^2

b=380; %nominal coolant flow in ml/min
Fco=b/1000000/60; %nominal flow rate in L/s

e=(A1*L1+A2*L2+A3*L3)/Fco;

%%
Tp=14.285; %time constant
```

Page | 129

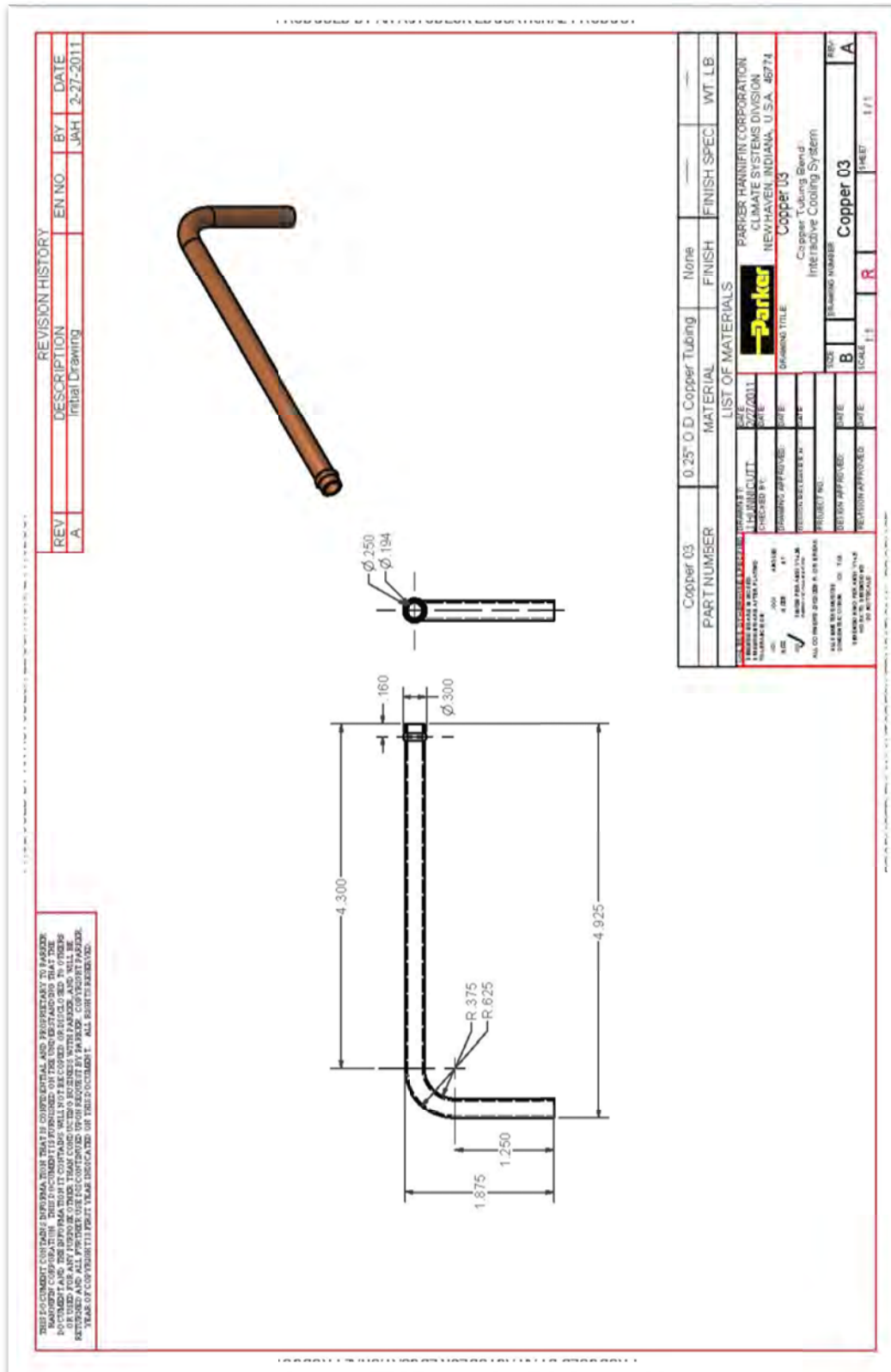
[illegible]

F-1: COPPER 01

Page | 130

Technical drawing of a copper tubing part, showing a side view with dimensions and a cross-section view. The side view shows a U-shaped tube with a horizontal section of 2.250, a vertical section of 3.850, and a total height of 2.289. The cross-section shows a tube with an outer diameter of 250 and an inner diameter of 194. The drawing is labeled 'Copper 02' and 'Copper 02'.

F-3: COPPER 03



[illegible]

REVISION HISTORY			
REV	DESCRIPTION	EN NO.	BY DATE
A	Initial Drawing		JAH 2-27-2011

Copper 05-2	0.25" O.D. Copper Tubing	None	FINISH	FINISH SPEC	WT. LB.
LIST OF MATERIALS Parker PARKER TUBING CORPORATION CUMMINS SYSTEMS DIVISION NEW HAVEN, INDIANA, U.S.A. 46774 DRAWING TITLE: Copper US-2 Copper Tubing Bend Interactive Cooling System					
PART NUMBER 0520011		DATE 02/27/2011			
CHECKED BY JAH		DATE 02/27/2011			
DESIGNED BY JAH		DATE 02/27/2011			
PROJECT NO. 0520011		DATE 02/27/2011			
DESIGN APPROVED JAH		DATE 02/27/2011			
TUBE B		DRAWING NUMBER Copper 05-2			
SCALE 1:1		R		SHEET 1/1	

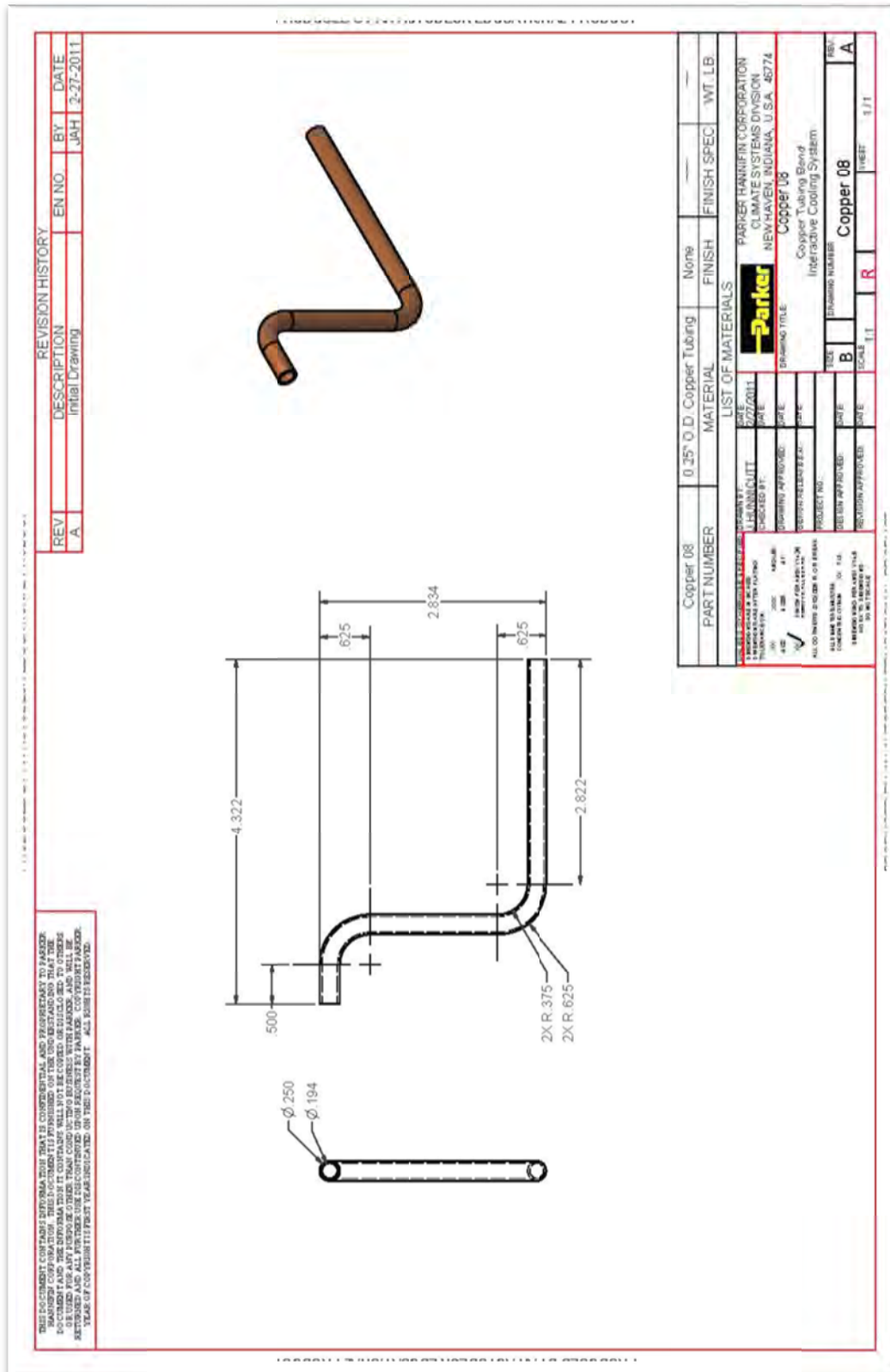
F-7: COPPER 05-3

REVISION HISTORY			
REV	DESCRIPTION	EN NO.	BY DATE
A	Initial Drawing		JAH 2-27-2011

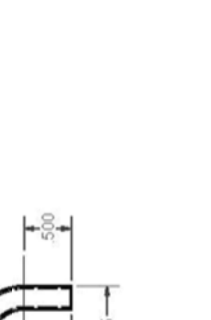
Copper 05-2	0.25" O.D. Copper Tubing	None	FINISH	FINISH SPEC	WT. LB.														
PART NUMBER																			
<div style="display: flex; justify-content: space-between;"> <div> <p>REVISIONS</p> <table border="1"> <thead> <tr> <th>REV</th> <th>DESCRIPTION</th> <th>DATE</th> </tr> </thead> <tbody> <tr> <td>1</td> <td>Initial Drawing</td> <td>2/27/2011</td> </tr> </tbody> </table> </div> <div> <p>LIST OF MATERIALS</p> <table border="1"> <thead> <tr> <th>ITEM</th> <th>DESCRIPTION</th> <th>QTY</th> <th>UNIT</th> </tr> </thead> <tbody> <tr> <td>1</td> <td>0.25" O.D. Copper Tubing</td> <td>1</td> <td>FT</td> </tr> </tbody> </table> </div> </div>						REV	DESCRIPTION	DATE	1	Initial Drawing	2/27/2011	ITEM	DESCRIPTION	QTY	UNIT	1	0.25" O.D. Copper Tubing	1	FT
REV	DESCRIPTION	DATE																	
1	Initial Drawing	2/27/2011																	
ITEM	DESCRIPTION	QTY	UNIT																
1	0.25" O.D. Copper Tubing	1	FT																


Copper 05-3		Copper Tubing Bend		Interactive Cooling System															
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REV	DESCRIPTION	DATE																	
1	Initial Drawing	2/27/2011																	
ITEM	DESCRIPTION	QTY	UNIT																
1	0.25" O.D. Copper Tubing	1	FT																

F-10: COPPER 08



REVISION HISTORY			
REV	DESCRIPTION	EN NO.	BY DATE
A	Initial Drawing		JAH 2-27-2011





NOTES:

1. ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED.
2. TOLERANCES: FRACTIONS - 1/16" MINIMUM; DECIMALS - 0.005" MINIMUM.
3. ALL DIMENSIONS SHOWN ON THIS DRAWING ARE TO BE MAINTAINED.
4. ALL DIMENSIONS SHOWN ON THIS DRAWING ARE TO BE MAINTAINED.
5. ALL DIMENSIONS SHOWN ON THIS DRAWING ARE TO BE MAINTAINED.

Copper 09		0.25" O.D. Copper Tubing		None		FINISH SPEC		WT. LB.	
PART NUMBER		MATERIAL		FINISH		FINISH SPEC		WT. LB.	
LIST OF MATERIALS									
ITEM NO.		QTY		UNIT		DATE		DATE	
1		1		ELBOW		02/27/2011		02/27/2011	
2		1		TUBING		02/27/2011		02/27/2011	
3		1		TUBING		02/27/2011		02/27/2011	
4		1		TUBING		02/27/2011		02/27/2011	
5		1		TUBING		02/27/2011		02/27/2011	
6		1		TUBING		02/27/2011		02/27/2011	
7		1		TUBING		02/27/2011		02/27/2011	
8		1		TUBING		02/27/2011		02/27/2011	
9		1		TUBING		02/27/2011		02/27/2011	
10		1		TUBING		02/27/2011		02/27/2011	
11		1		TUBING		02/27/2011		02/27/2011	
12		1		TUBING		02/27/2011		02/27/2011	
13		1		TUBING		02/27/2011		02/27/2011	
14		1		TUBING		02/27/2011		02/27/2011	
15		1		TUBING		02/27/2011		02/27/2011	
16		1		TUBING		02/27/2011		02/27/2011	
17		1		TUBING		02/27/2011		02/27/2011	
18		1		TUBING		02/27/2011		02/27/2011	
19		1		TUBING		02/27/2011		02/27/2011	
20		1		TUBING		02/27/2011		02/27/2011	
21		1		TUBING		02/27/2011		02/27/2011	
22		1		TUBING					

Technical drawing of a copper tubing bend. The drawing includes a perspective view of the bend, a side elevation view showing a 1.000 inch length and a 2.000 inch diameter, and a cross-sectional view showing an outer diameter of 0.375 inches and an inner diameter of 0.305 inches. A fillet radius of R.125 is indicated at the bend. The drawing is titled 'Copper 11' and includes a revision history table.

REV	DESCRIPTION	EN NO.	BY	DATE
A	Initial Drawing		JAH	2-27-2011

F-14: COPPER 12

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REVISION HISTORY

REV	DESCRIPTION	EN NO	BY	DATE
A	Initial Drawing		JAH	2-27-2011

3D Model View

750

2D Section View

Ø 375
Ø 305

LIST OF MATERIALS

PART NUMBER	0.375" O.D. Copper Tubing	None	FINISH	FINISH SPEC	WT. LB
Copper 12					

—Parker—

PARKER HANFMAN CORPORATION
CLIMATE SYSTEMS DIVISION
NEW HAVEN, INDIANA, U.S.A. 46774

Copper 12
Copper Tubing Band
Interactive Cooling System

SCALE: 3:1

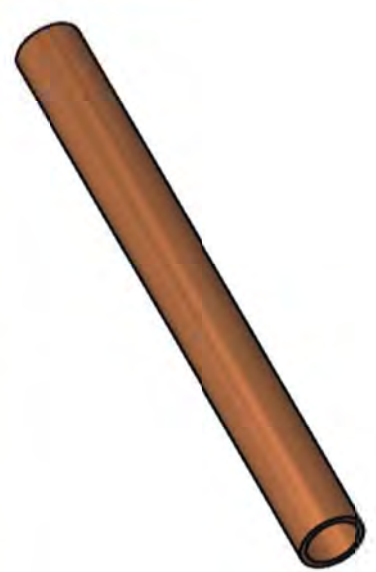
SHEET 1 OF 1

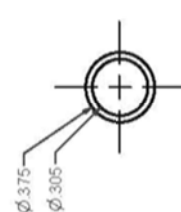
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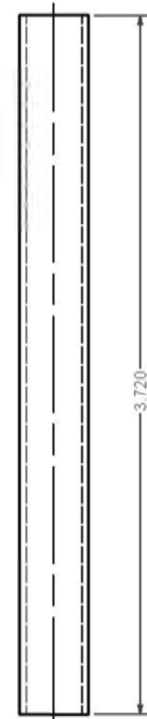
F-15: COPPER 13

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REVISION HISTORY			
REV	DESCRIPTION	EN NO	BY DATE
A	Initial Drawing		JAH 2-27-2011







PART NUMBER	0.375" O.D. Copper Tubing	None	FINISH	FINISH SPEC	WT. LB.
Copper 01					

LIST OF MATERIALS

ITEM NO.	DESCRIPTION	QTY	UNIT	DATE
1	0.375" O.D. Copper Tubing	1	FT	2/27/2011

APPROVALS

DESIGNED BY	CHECKED BY	DATE	DESIGNED BY	CHECKED BY	DATE

REVISIONS

REV	DESCRIPTION	DATE
A	Initial Drawing	2/27/2011

SCALE

SCALE	DATE
1" = 1'-0"	2/27/2011

REVISION NUMBER

REV	DATE
A	2/27/2011

COMPANY

COMPANY	DATE
PARKER HANNIFIN CORPORATION	2/27/2011

LOCATION

LOCATION	DATE
CLIMATE SYSTEMS DIVISION	2/27/2011

PROJECT

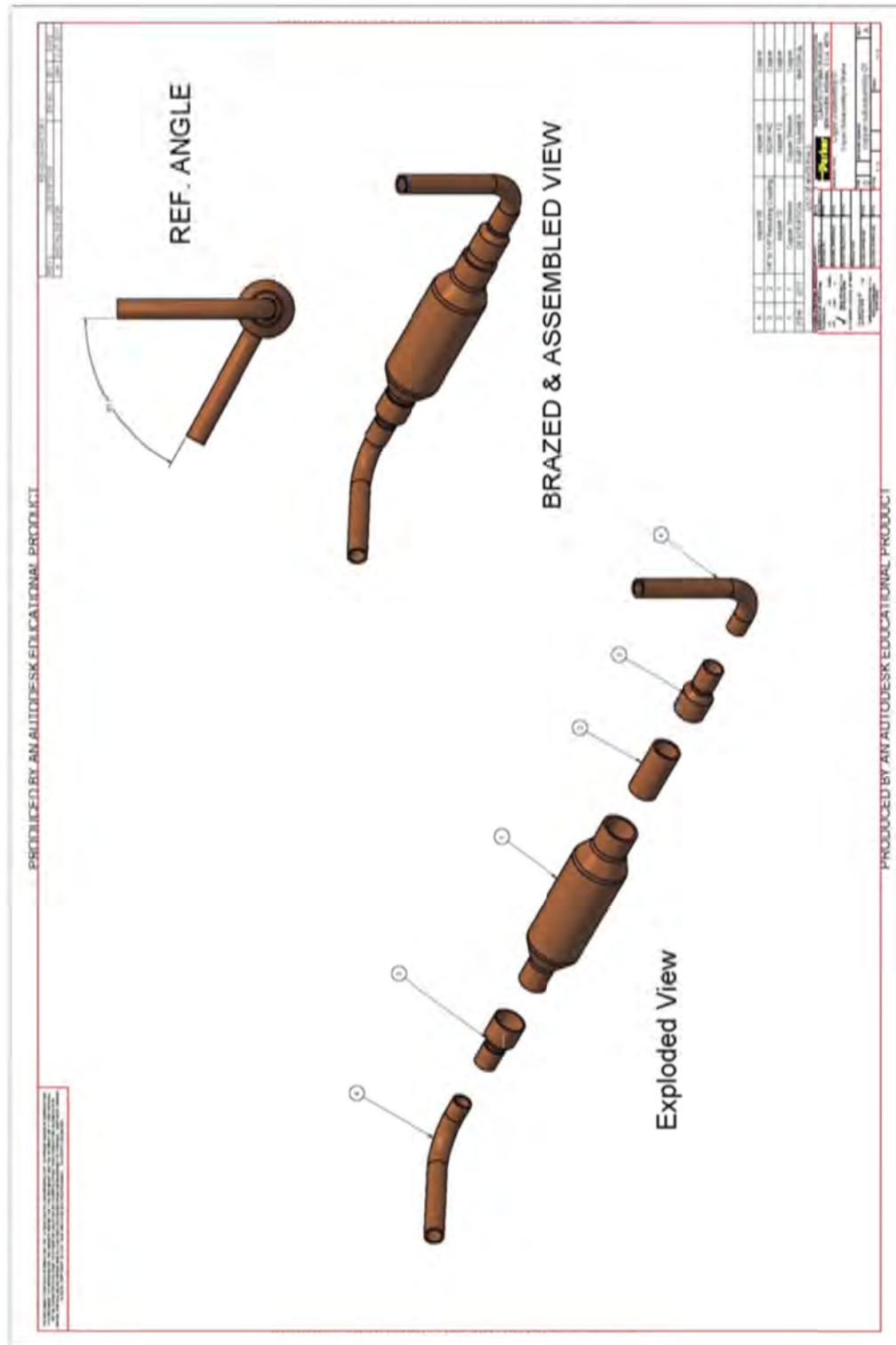
PROJECT	DATE
Copper Tubing Bend	2/27/2011

INTERACTIVE COATING SYSTEM

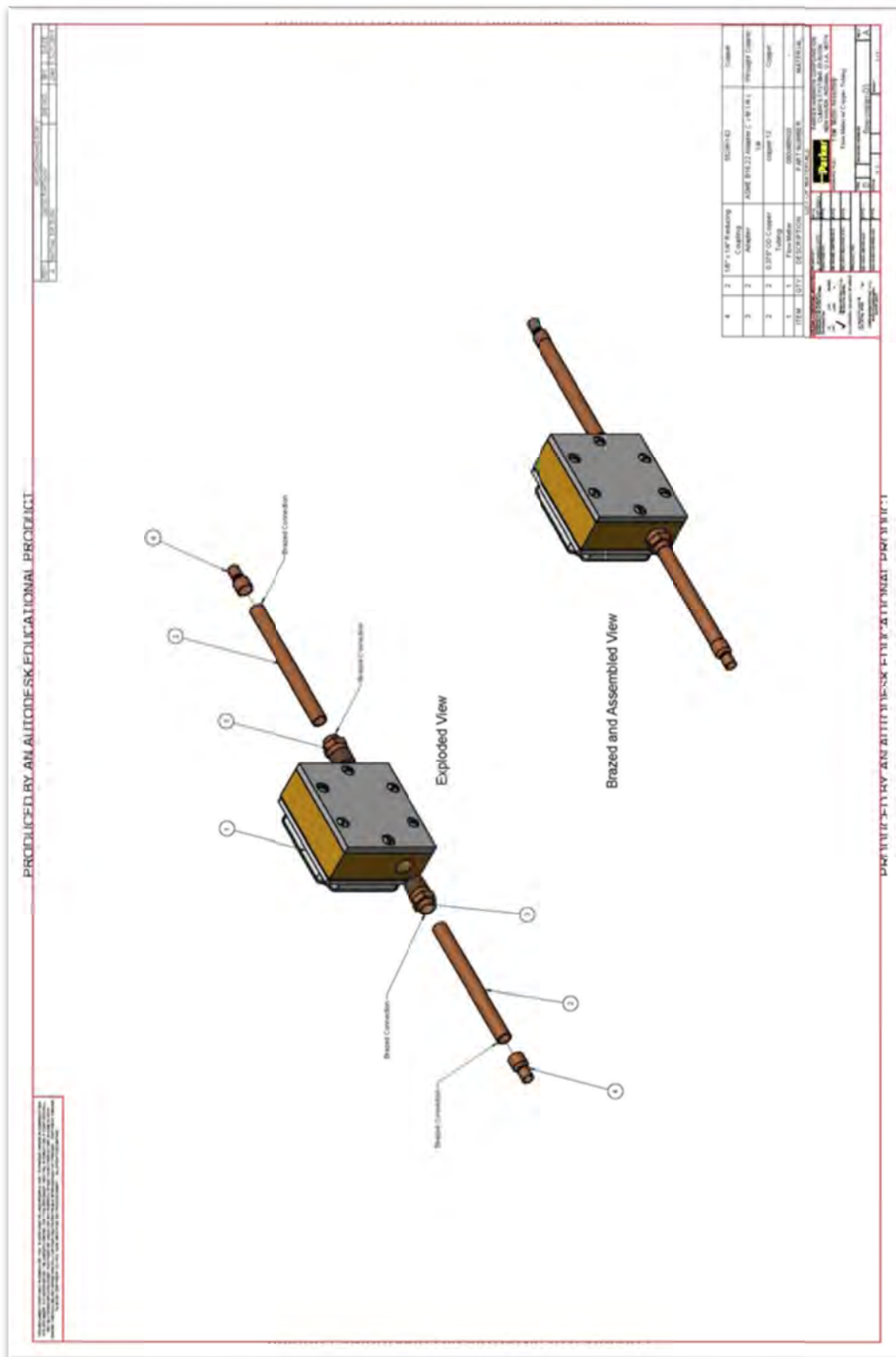
INTERACTIVE COATING SYSTEM	DATE
Copper 13	2/27/2011

APPENDIX G: SUB-ASSEMBLIES

G-1: STRAINER SUB-ASSEMBLY



G-2: FLOW METER SUB-ASSEMBLY



G-3: SAFETY-VALVE SUB-ASSEMBLY

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REV A DESCRIPTION Initial Drawing EN NO. JAH BY DATE 2-27-2011

REVISION HISTORY

EXPLODED VIEW

BRAZED AND ASSEMBLED VIEW

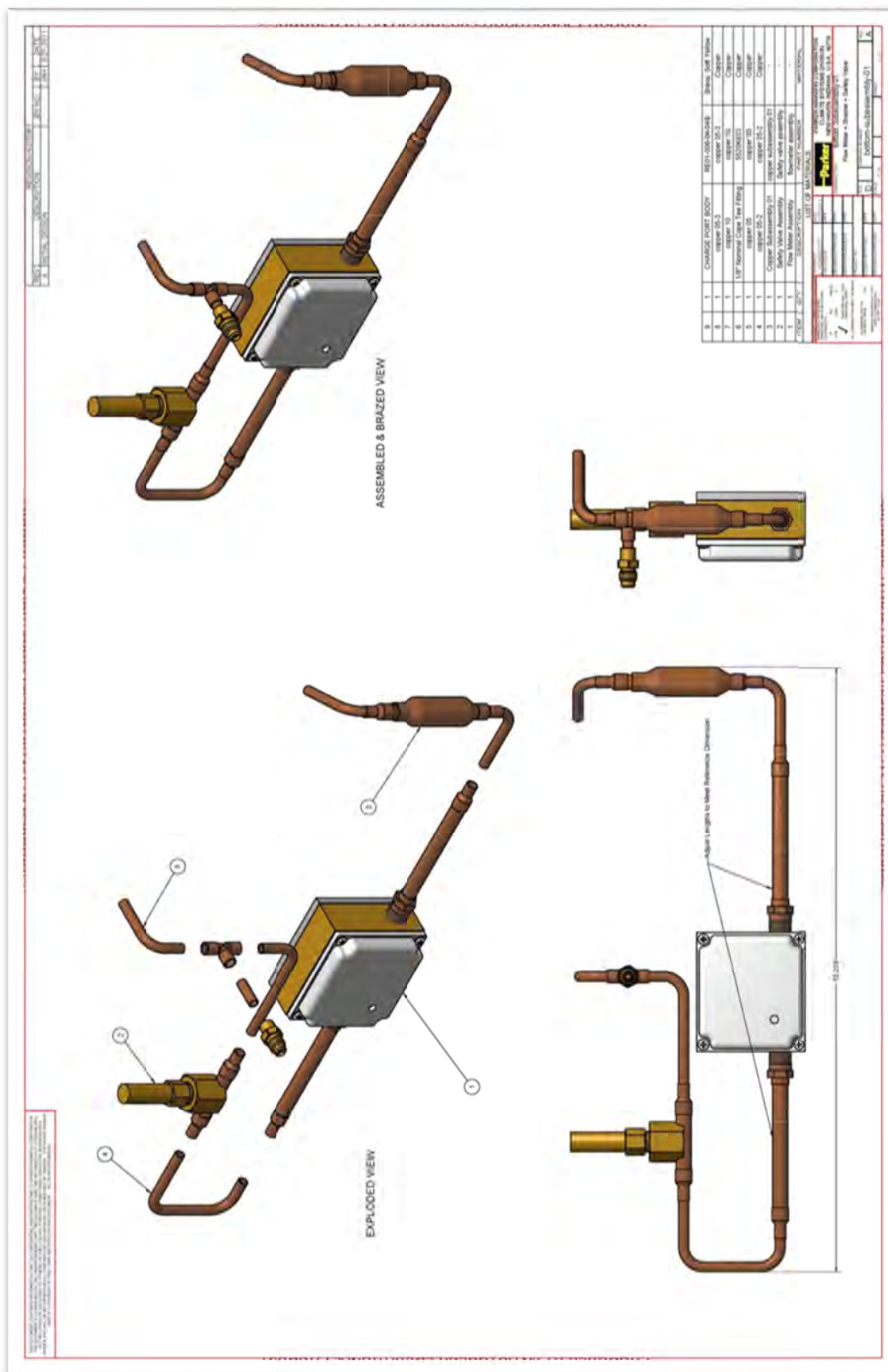
LIST OF MATERIALS

ITEM	QTY	DESCRIPTION	PART NUMBER	MATERIAL
4	2	1/8" to 1/4" Nom Pipe Reducing Coupling	5520K142	Copper
3	1	copper 11	copper 11	Copper
2	1	0.375" OD Saddle to 7/16" UNC Adapter	PCC-SY-010	Brass, Soft Yellow
1	1	450 PSIG Safety Valve with 7/16" Thread	PCC-QM-019	Brass, Soft Yellow

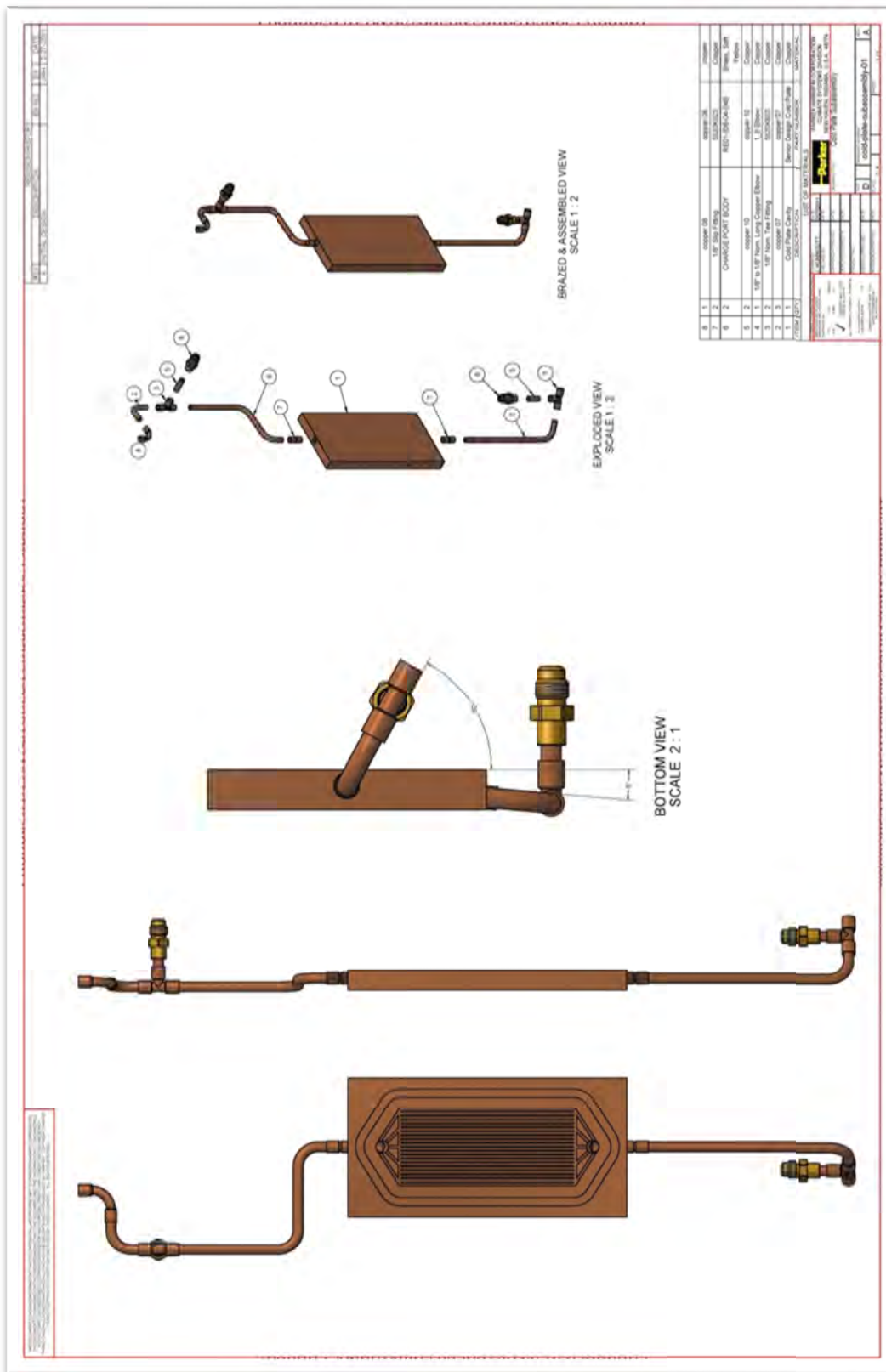
DATE: 02/27/11
 DRAWN BY: JAH
 CHECKED BY: JAH
 DESIGNED BY: JAH
 PROJECT NO.: 450 PSIG
 INTERACTIVE COOLING SYSTEM
 SAFETY VALVE-01
 SCALE: 1" = 1"

PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT

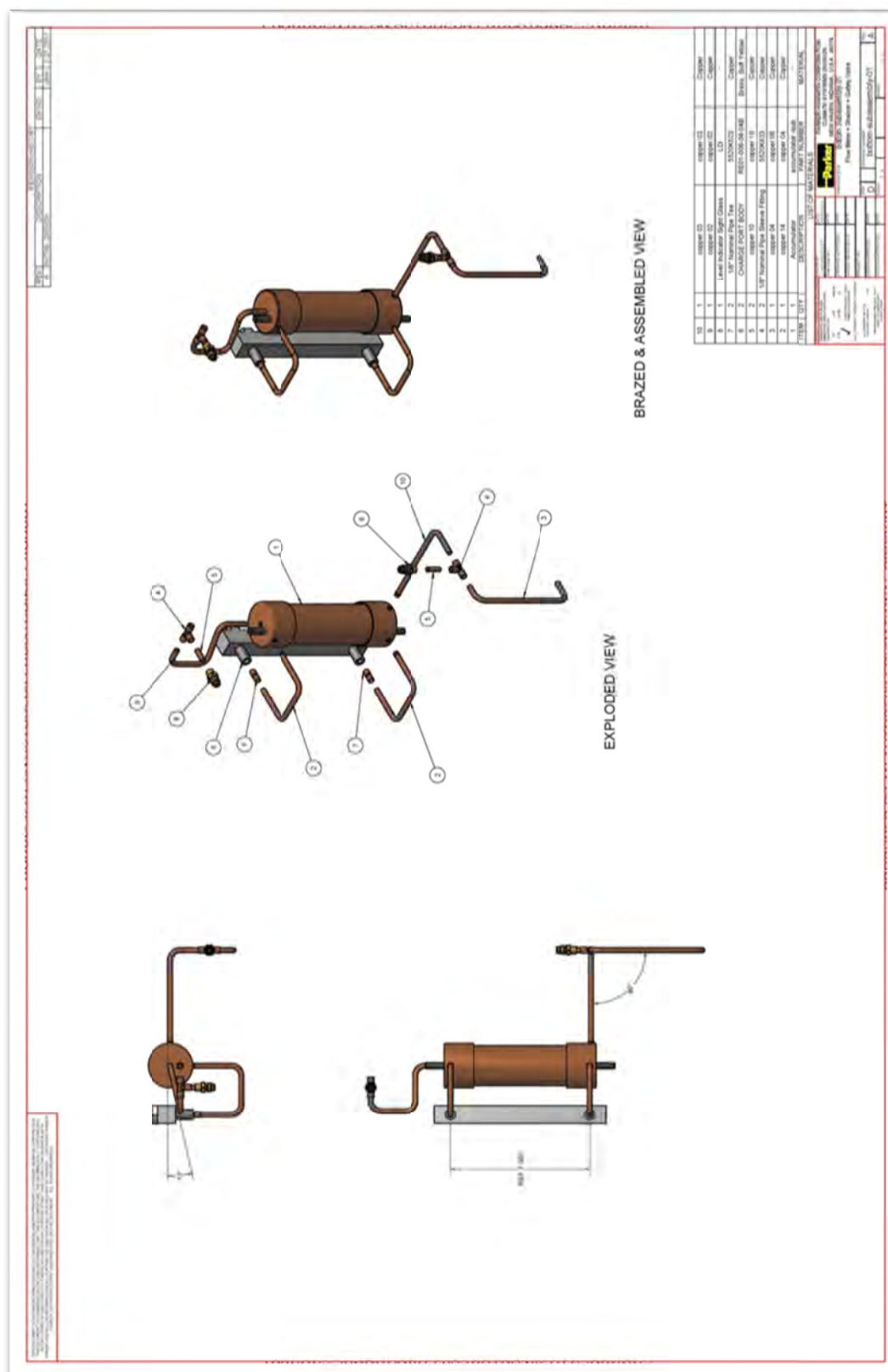
G-4: BOTTOM CYCLE SUB-ASSEMBLY



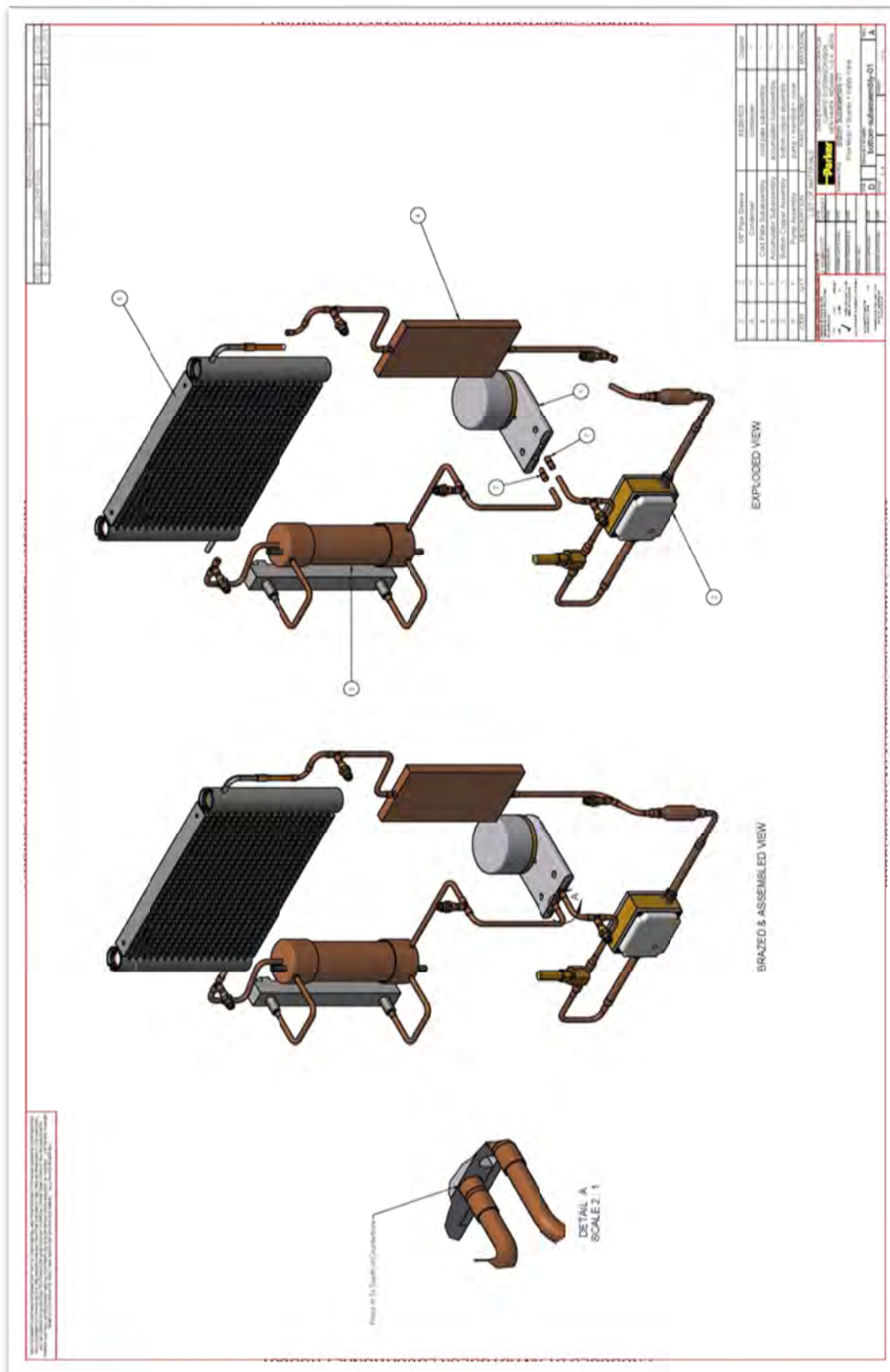
G-5: COLD PLATE SUB-ASSEMBLY



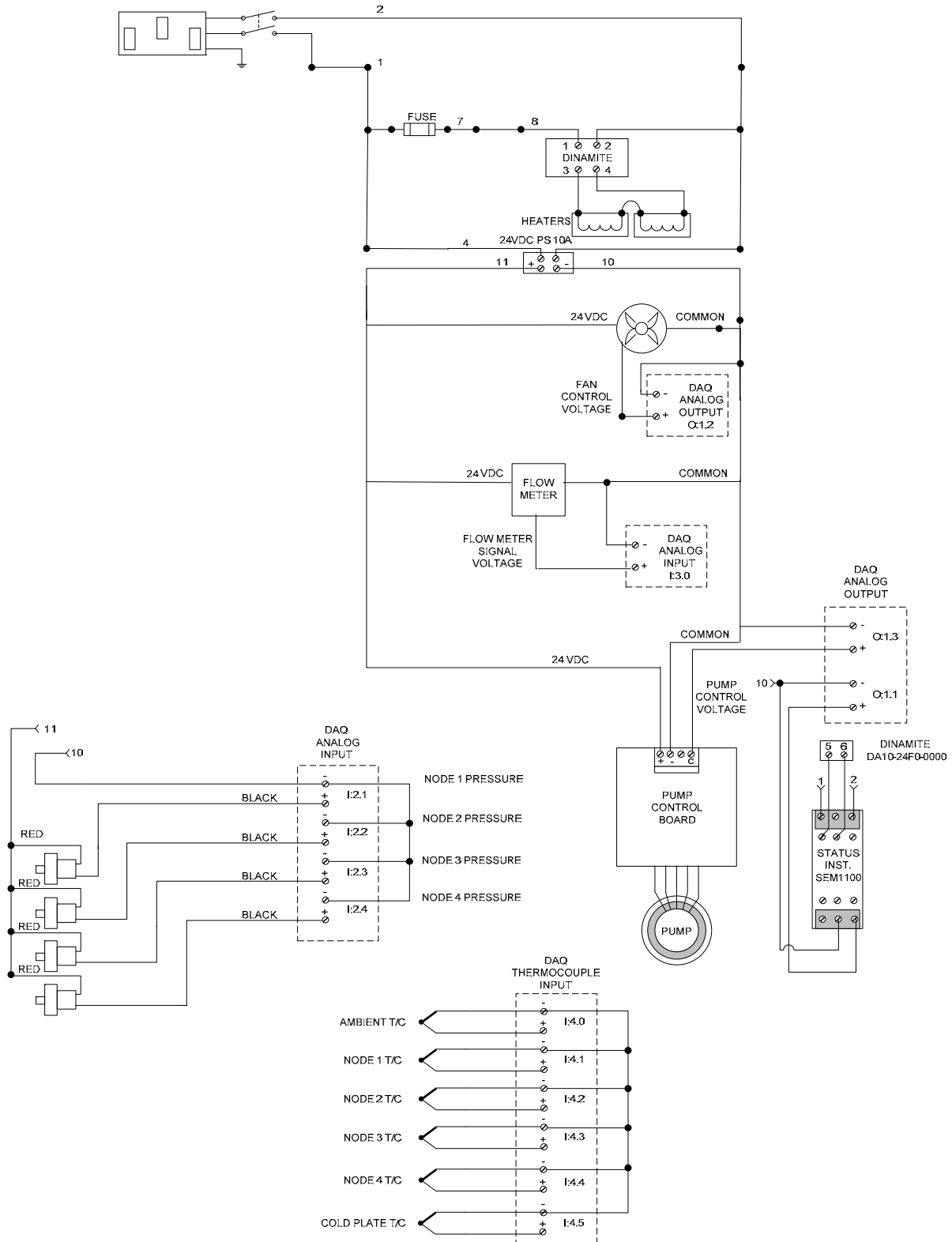
G-6: ACCUMULATOR SUB-ASSEMBLY



G-7: FINAL BRAZING ASSEMBLY



APPENDIX H: CONNECTION DIAGRAM FOR THE ICS



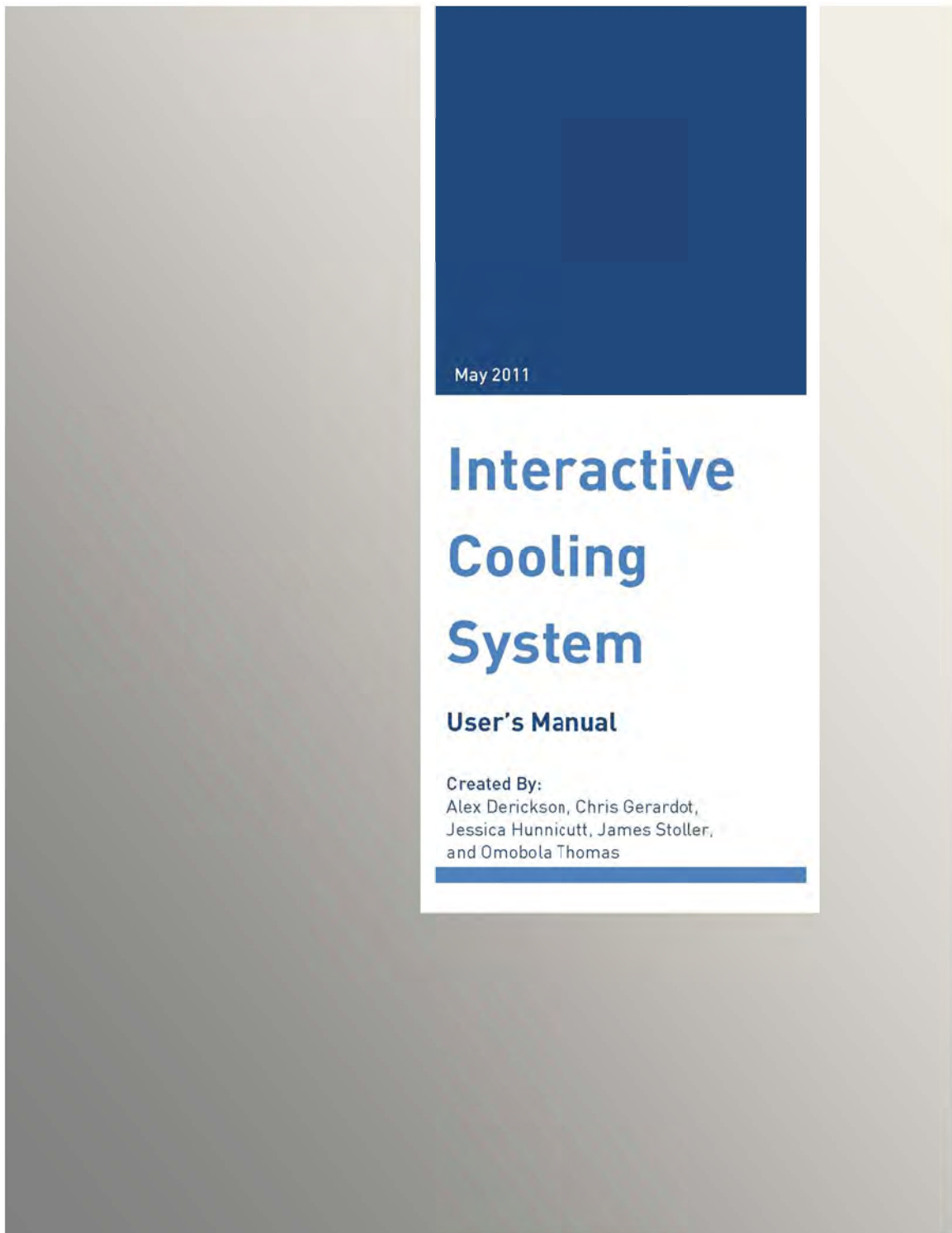


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ICS User Manual

Running the ICS

Getting to Run-time Environment (Option 1)

1. Plug in female end of cord to power entry module on the left back side of unit and the male end of cord to a standard wall outlet. See Figure 1 and 2.



Figure 1 - Plug Power Cord into Standard Outlet



Figure 2 - Plug Female End of Power Cord into Power Entry Module of ICS

2. Flip switch to ON position on power entry module. Figure 3 shows the power entry module in the ON position.



Figure 3 - Power Button Switch

3. Open rear cabinet doors.

4. Press power button on CPU. See Figure 4 below.



Figure 4 - CPU Power Button

5. Close rear cabinet doors.
6. Go to the front of the ICS and type in password on screen if prompted (ipfw).
7. Double click on the black and white *Parker* icon on the desktop as shown in Figure 5.



Figure 5 - Desktop View

8. If any license window pops up as shown in Figure 6, just close it.



Figure 6 - InteractX Run Startup Service Window

9. The application should be running now. See Figure 7.

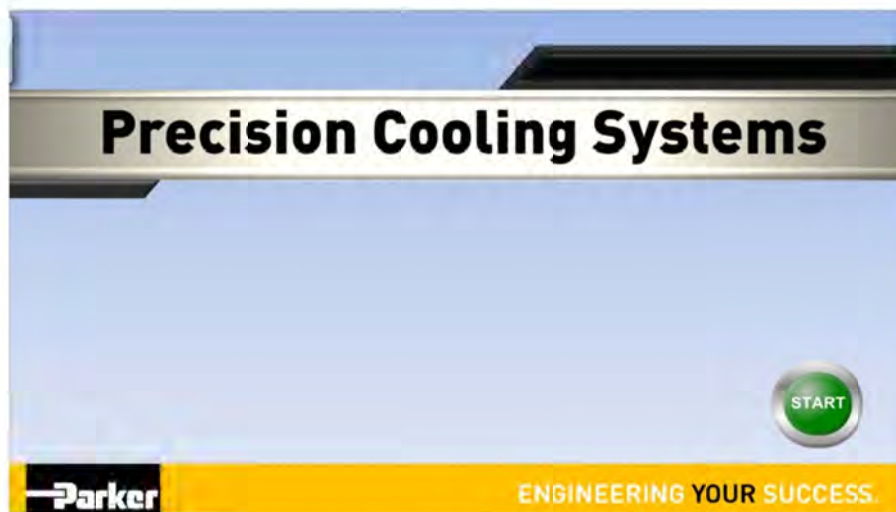


Figure 7 - Application is Now Running

Getting to Run-time Environment (Option 2)

1. Follow option 1 from steps 1 through 6.
2. Double click on the *Machine Shop Suite* icon on the desktop as shown in the red circle in Figure 8.



Figure 8 - Desktop View

3. Click the icon corresponding to *Open an Existing Machine Shop Project*. See Figure 9.

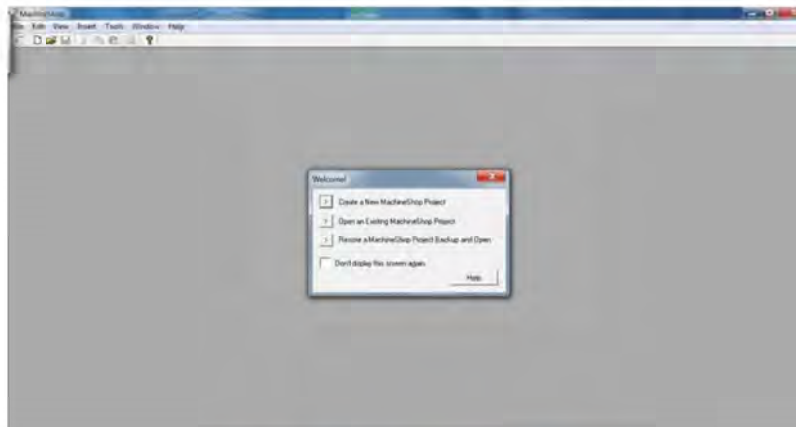


Figure 9 - MachineShop Welcome Window

4. Make sure the Project location displayed is *C:\Program Files\Machine Shop Suite\Projects*. See Figure 10.

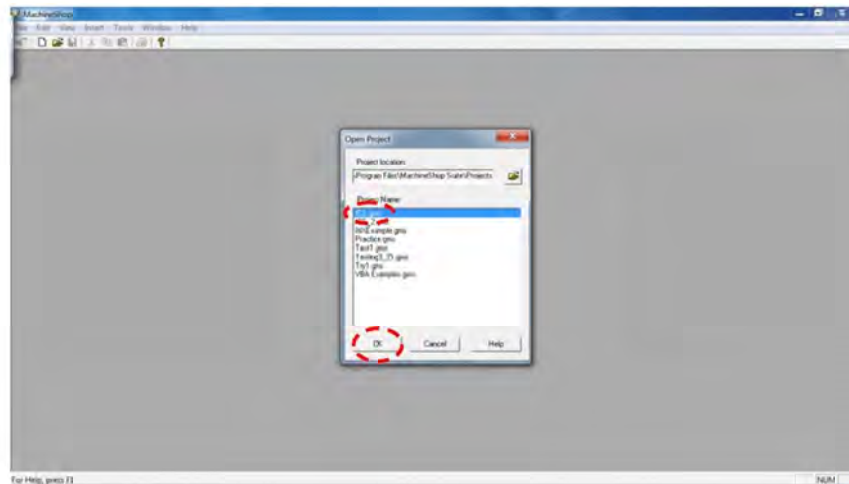


Figure 10 - Open Project Window

5. Click on *ICS.gms* and select *OK*. See Figure 11. Note: If a "Project Recovery" window appears, press "Resume".

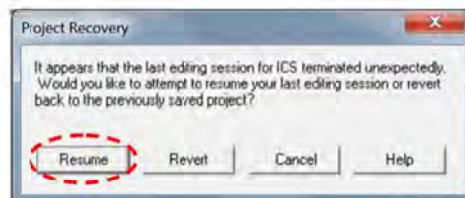


Figure 11 - Project Recovery

6. In the Project Browser window, expand the tree if needed and double-click *ICS* with the pink diamond icon which is under *Interact X* (under *kh*, under *ICS*). See Figure 12.



Figure 12 - ICS Project File Welcome Screen

Note: If the Project Browser window is not visible, go to View and select "Application Browser".

7. If any license window pops up like Figure 13 below, just close it.



Figure 13 - InteractX Run Startup Service Window

8. On the Menu Bar, select Tools -> Run Application, alternatively click the green forward arrow (circled in red) on the task bar. See Figure 14.



Figure 14 - Starting Application

9. Click *Connected* (not *Offline*).
10. Again, if a license window pops up as in Figure 13 above, close it.
11. The application should be running now.

Demonstrating the 2-phase precision cooling technology

1. Click the *START* button on the screen to start the process. See Figure 15.



Figure 1 - Home Screen of ICS Application

2. Click *BEGIN*. See Figure 16.

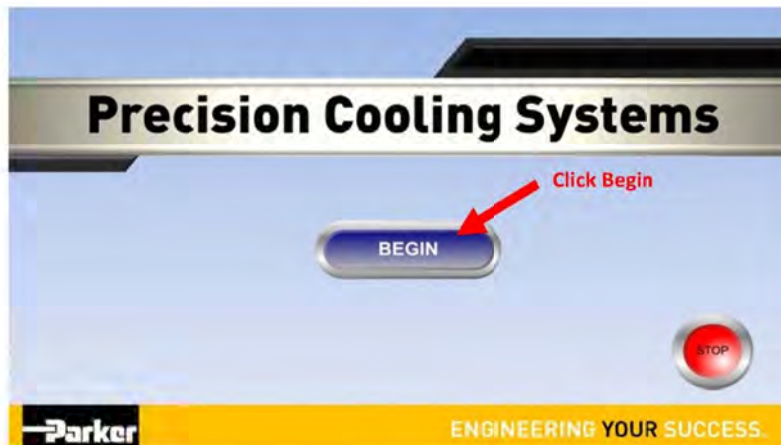


Figure 2 - Beginning Application

3. Select the device you would like to cool based on the heat load and desired temperature descriptions given. Alternatively, select *CUSTOM* in order to specify your heat load and desired temperature inputs. See Figure 17.

	DEVICE 1	DEVICE 2	DEVICE 3	CUSTOM
Heat Load (Q)	200	500	800	?
Desired Temperature (°C)	42	60	65	?

Figure 17 - Selection of Cooling Needs

4. If one of the preset devices has been selected or the *CUSTOM* button was selected, the *CONTINUE* button will show up, otherwise it will not show up. Click *CONTINUE* to continue. See Figure 18 for how the screen locks after *CUSTOM* has been selected. If one of the preset devices was selected, skip to step 8.

	DEVICE 1	DEVICE 2	DEVICE 3	CUSTOM
Heat Load (Q)	200	500	800	?
Desired Temperature (°C)	42	60	65	?

Figure 18 - Selecting Custom Setting

5. If *CUSTOM* was selected, you have to click the heat load corresponding what you want to cool. This value shows up in the display window. Figure 19 shows the screen when a heat load of 500 W was selected. If satisfied, click *CONTINUE*.



Figure 19 - Select Custom Heating Load

6. Select your desired temperature. This value shows up in the display window. Figure 20 shows the screen when a desired temperature of 55 C was selected. If satisfied, click *CONTINUE*.

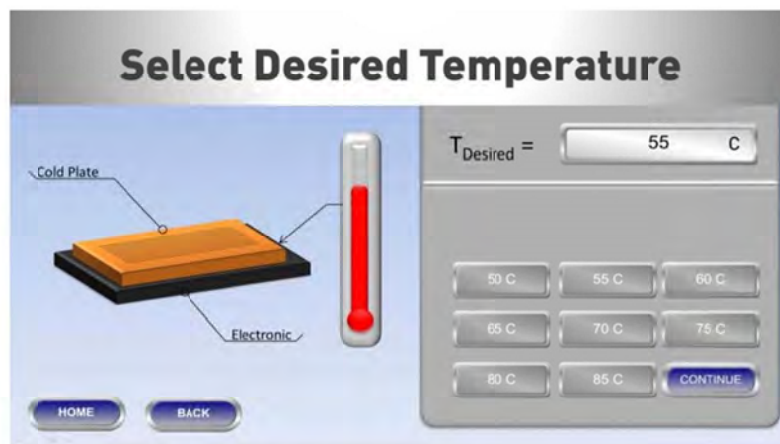


Figure 20 - Selecting Desired Temperature

7. This page shows you the parameters you selected. If satisfied, click *CONTINUE*, if not click *BACK*. See Figure 21.

The screenshot displays a software interface titled "Get Ready to Cool!". Below the title, it says "CUSTOM DEVICE" and "Selected Input Parameters". There are two input fields: "Heat Load (W)" with a value of 500, and "Desired Temperature (C)" with a value of 55. At the bottom, there are three buttons: "HOME", "BACK", and "CONTINUE". The Parker logo and the tagline "ENGINEERING YOUR SUCCESS." are visible at the bottom of the interface.

Parameter	Value
Heat Load (W)	500
Desired Temperature (C)	55

Figure 21 - Verifying Heat and Temperature Inputs

8. This page gives a variety of activities that the user can do. They include viewing a temperature at the cold plate vs. time graph (***Temperature Chart***), viewing the temperature and pressure at each node (***Summary Page***), viewing advanced calculations such as enthalpy, entropy, and so on (***Advanced Calculations***), starting or stopping the data logging process (***Start Logging***), viewing pictures of the ICS team (***Meet the Designers***), and viewing contact information for Parker Hannifin (***Contact Information***). After each option, the user can press the ***BACK*** button in to choose another activity (except for the data logging button which doesn't go to a different screen but just starts and stops the data logging process with each click). See Figure 22.



Figure 22 - Cooling Screen

9. If the **Temperature Chart** button is chosen, a screen similar to what is shown in Figure 23 should appear. The temperature readings at 0 seconds are the current readings. You can increase the amount of data points viewed by clicking the button circled in red and typing the amount of data points you want.

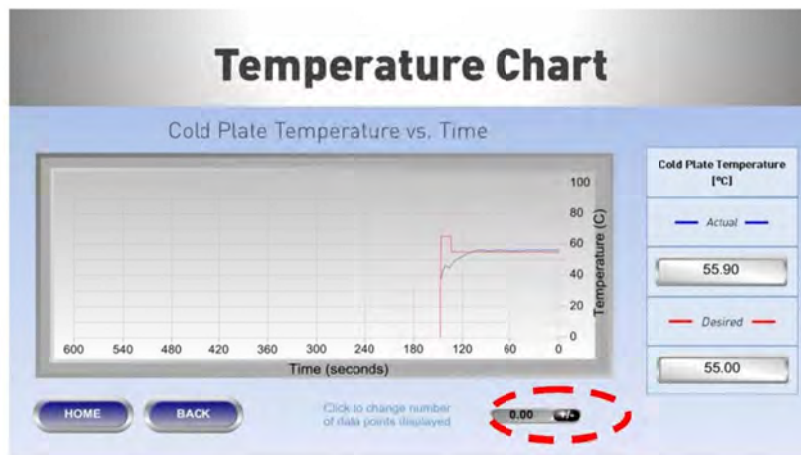


Figure 23 - Temperature Chart Screen

The blue line shows the actual temperature at the cold plate while the red line shows the desired temperature selected- 55 C.

10. If the **Summary Page** button is chosen, a screen similar to what is shown in Figure 24 should appear. The temperature and pressure at each node as well as ambient, desired and cold plate temperature will be displayed.

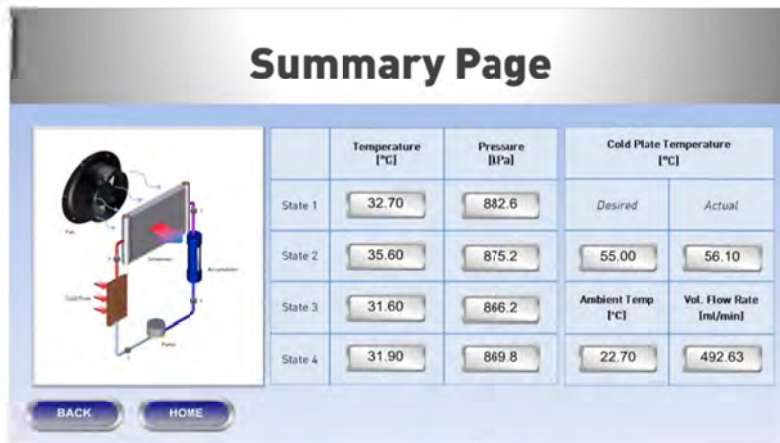


Figure 24 - Summary of Sensor Data

11. If the **Advanced Calculations** button is chosen, a screen similar to what is shown in Figure 25 should appear. Enthalpy and Entropy at each node/state as well as volumetric flow rate of the refrigerant and the quality of the refrigerant will be displayed.

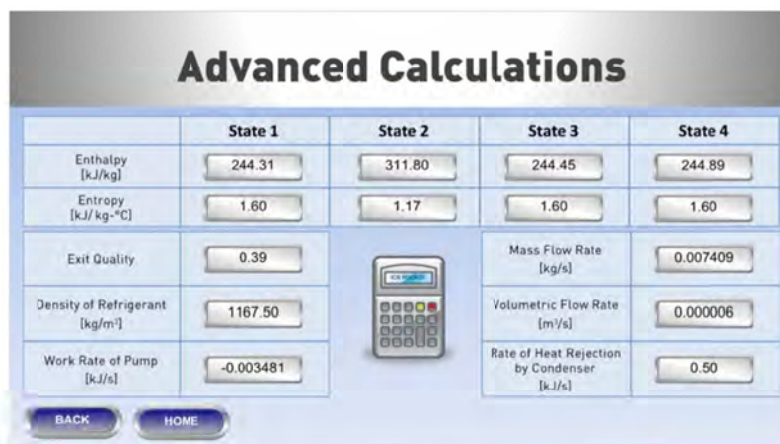


Figure 25 - Advanced Thermodynamic Properties Calculated

12. If the **Start Logging** button is chosen, the screen still remains the same but the data logging will begin. After one has exit the run time environment, the data will be stored on

the desktop in a Microsoft Access file called Data. To stop data logging just click the **Start Logging** button again (which by this time will read **Stop Logging**). Figure 26 shows a screen shot of some sample data collected.

Video Data											
Today	Moment	Heatload	DesiredTemp	TempCP	Temp1	Temp2	Temp3	Temp4	AmbientTemp	Pressure	TA
8/21/2011	8:12:11 PM	500	80	57.3	34.9	39.3	37.8	37.9	23.4	1092.9571875	
8/21/2011	8:12:12 PM	500	80	57.8	34.9	39.3	37.9	37.9	23.3	1099.20978125	
8/21/2011	8:12:13 PM	500	80	57.8	35	39.4	37.9	38	23.4	1094.1815625	
8/21/2011	8:12:13 PM	500	80	61.8	35.4	41	39.5	39	23.4	1128.84078125	
8/21/2011	8:12:14 PM	500	80	62.1	35.4	41.1	39.7	39.1	23.4	1133.13015625	
8/21/2011	8:12:15 PM	500	80	62.1	35.4	41.2	39.7	39.2	23.4	1136.811125	
8/21/2011	8:12:16 PM	500	80	62.3	35.5	41.2	39.8	39.1	23.4	1141.31796875	
8/21/2011	8:12:17 PM	500	80	62.5	35.5	41.4	40	39.3	23.5	1146.07828125	
8/21/2011	8:12:18 PM	500	80	62.6	35.5	41.4	40	39.3	23.5	1150.34796875	
8/21/2011	8:12:19 PM	500	80	62.8	35.7	41.6	40.1	39.4	23.4	1154.9125	
8/21/2011	8:12:40 PM	500	80	63	35.6	41.8	40.2	39.5	23.4	1158.7909375	
8/21/2011	8:12:41 PM	500	80	63.1	35.6	41.7	40.4	39.6	23.4	1162.8848375	
8/21/2011	8:12:42 PM	500	80	63.8	35.7	41.8	40.4	39.6	23.4	1167.840625	
8/21/2011	8:12:43 PM	500	80	63.4	35.7	41.9	40.5	39.7	23.4	1171.288125	
8/21/2011	8:12:44 PM	500	80	63.6	35.8	42.1	40.6	39.8	23.4	1175.81296875	
8/21/2011	8:12:45 PM	500	80	63.7	35.8	42.1	40.7	39.9	23.3	1180.1224375	
8/21/2011	8:12:46 PM	500	80	63.8	35.8	42.2	40.8	40	23.4	1184.21625	
8/21/2011	8:12:47 PM	500	80	64	35.8	42.3	40.9	40.1	23.4	1188.74109375	
8/21/2011	8:12:48 PM	500	80	64.2	35.9	42.3	41	40.2	23.4	1193.05046875	
8/21/2011	8:12:49 PM	500	80	64.3	35.9	42.5	41.1	40.2	23.4	1196.48796875	
8/21/2011	8:12:50 PM	500	80	64.5	35.9	42.6	41.2	40.3	23.4	1200.80734375	

Figure 26 - Sample of Data Collected

13. If the **Meet the Designers** button is chosen, Figure 27 is the screen that will be seen.

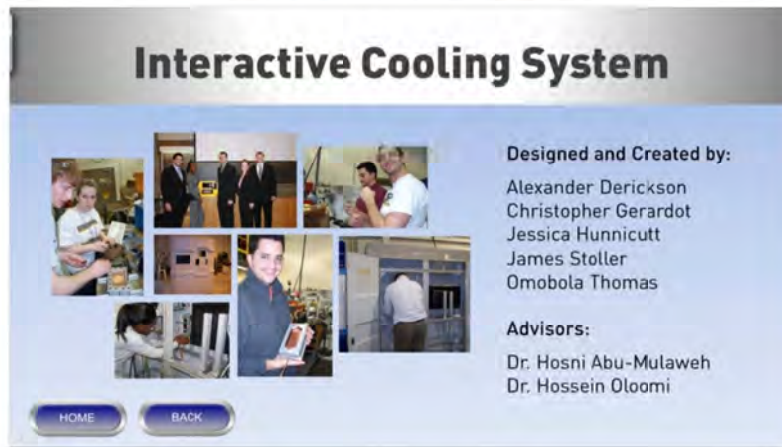


Figure 27 - Meet the Designers

14. If the **Contact Information** button is chosen, Figure 28 is the screen that will be seen.



Figure 28 - Contact Information

15. You can go back at any time to view different things or click *HOME* at any time to go back to the start screen to start over or to exit the application.

Exiting Run-time Environment

1. Click *HOME* from any screen (or *BACK* till you get to a screen with a *HOME* button and then click *HOME*) to go back to the start screen
2. Click the *STOP* button on the welcome page. This turns off the fan and resistive heaters. See Figure 29.



Figure 29 - Home Page

3. Now the *EXIT* button shows up. Click it to exit the run-time environment, alternatively if a keyboard is connected hit Alt-F4. See Figure 30.

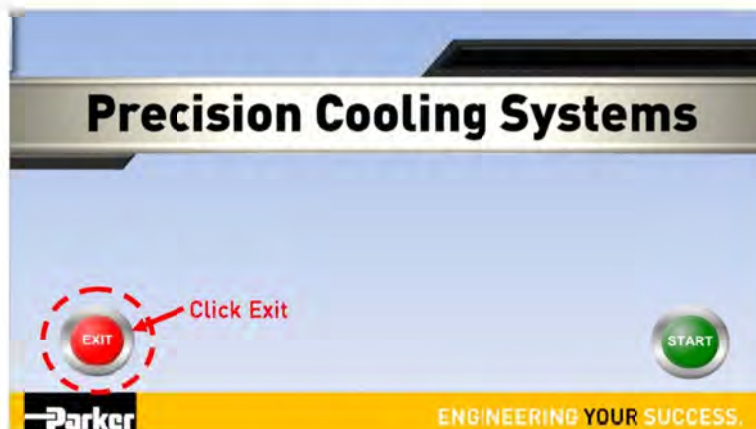


Figure 30 - Exit Screen

4. Close the Machine Shop Suite window (if it is open; usually happens if option 2 is used to get to run time environment).
5. Double click the *Shutdown* icon on the desktop as shown in Figure 31.



Figure 31 – Shutdown ICS

6. After the computer has shut down, flip the power entry module switch to the OFF position.
7. Unplug the power from the wall outlet.

How to Add/Remove Refrigerant from the ICS

How to Remove Refrigerant from the ICS

1. First, you need to gather three things before starting the physical evacuation of refrigerant from the ICS. You will need to get 2 refrigerant hoses, a recovery tank, and a recovery unit.

Note: All hoses and connections will require a 3/8" charge port or seal-rite. The hoses are typically 4-8ft. in length and should be able to hold at least 500psi burst pressure.

2. Attach seal-rites to the end of the refrigerant hoses. This is so you will not spray refrigerant or Krytox® oil upon connecting or disconnecting the hose from the ICS, recovery unit, or the recovery tank.
3. Attach one seal-rite to the ICS charge port located in the center of the mechanical system.
4. Attach the other end of the same hose to the recovery unit. Make sure that this hose is attached to the connection of the recovery unit denoted inlet.
5. Attach one end of the second hose to the last remaining connection of the recovery unit denoted outlet.
6. Attach the other end of the same hose to the connection on the recovery tank denoted liquid. If there is only one port on the recovery tank this distinction will not be made and connect to the only port on the tank.
7. Open the valve on the top of the recovery tank.
8. Check to make sure that both dials located near the connections denoted inlet and outlet of the recovery unit are set to the closed position.
9. Turn on your recovery unit.
10. First open the outlet dial of the recovery unit to the most open position.
11. Slowly open the inlet dial of the recovery unit. This is done slowly because at some point you might run into a situation where refrigerant and oil move too quickly through the recovery unit and it will make a loud "gargling" noise. If you hear this noise turn the dial slightly to the closed position until the noise goes away.
12. Wait until the gauge above the inlet dial starts to read in a pressure below 0psi or in micrometers.
13. Remove the seal-rite attached to the ICS.
14. Turn off the recovery unit.
15. Close the recovery tank.
16. You may now safely remove the hoses from both inlet and outlet of the recovery unit.
17. You have successfully recovered the ICS of refrigerant and oil.

Note: At this point you may safely remove components from the ICS if you wish.

How to Vacuum the ICS prior to Adding Refrigerant

1. First you will need to get three things before you can start the vacuuming of the ICS. You will need to get two hoses (preferably hose clean of oil, i.e. a hose not used in the recovery

or charging of the ICS. You may want to use one standard length hose and one may be less than one foot), a vacuum pump, and a micrometer.

2. Attach seal-rites to the end of the refrigerant hoses. This is so you will not allow the vacuumed pressure to be released from the ICS after you have properly pulled a vacuum.
3. Attach one seal-rite to the ICS charge port located in the center of the mechanical system.
4. Attach the other end of the same hose to one connection of the micrometer.
5. Attach one seal-rite of the second hose to the other connection of the micrometer.
6. Attach the other end of this hose to the only connection on the vacuum pump.
7. Turn on the micrometer if it is digital. If it is a physical gauge then you will skip this step.
8. Turn on the vacuum pump.
9. Wait until the micrometer is below 100 microns. If the micrometer will not go below 300-400 microns then the ICS is leaking and you will need to perform a "leak test".
10. Once the ICS is below 100 microns you can remove the seal-rite that is attached to the ICS.
11. Turn off the vacuum pump.
12. Turn off the micrometer.
13. Remove the seal-rite attached to the vacuum pump.
14. You may now safely remove the hoses from both ends of the micrometer.
15. You have successfully pulled a vacuum on the ICS.

Note: At this point you should be ready to charge the ICS with refrigerant.

Adding Refrigerant to the ICS

1. First you will need to gather 9 things. You will need to get two refrigerant hoses, a tank of clean R-134a refrigerant, a scale capable of measuring precisely how much refrigerant is removed from the refrigerant tank, an oil injector because the ICS charge port is not upright, Krytox® oil or comparable, a valve to open/close the flow of refrigerant, two 3/8" male to male adapters (like a double sided charge port), a 3/8" plastic sealing cap, and possibly a hand help electric heater.
Note: Clean refers to refrigerant without oil. This refrigerant should be pure.
2. Attach seal-rites to the end of the refrigerant hoses. This is so you will not spray refrigerant or Krytox® oil upon connecting or disconnecting the hose from the ICS, recovery unit, or the recovery tank.
3. Attach the male to male adapter to one side of the oil injector.
4. Cap off one end of the oil injector with a plastic or brass cap. Plastic is preferred.
5. Fill you oil injector with the desired amount of oil while keeping the capped off end pointing down.
6. Attach one end of the of the oil injector hose to the last remaining male to male adapter.
7. Attach the male to male adapter to one side of the refrigerant flow valve (Make sure the refrigerant flow valve is closed).
8. Attach the other end of the refrigerant flow valve to a seal-rite connected to a hose.
9. Attach the other end of the hose, with seal-rite, to the ICS charge port.
10. Now you can turn the capped off end of the oil injector in the upright direction. This will allow the oil to move toward the refrigerant flow valve.
11. Remove the plastic cap attached to the oil injector's male to male adapter.
12. Attach a seal-rite to the male to male adapter of the oil injector.
13. Attach the other end of the hose, with seal-rite, to the clean refrigerant tank. (Make sure the tank is still in the closed position.)
14. Inspect the refrigerant tank to determine which side needs to be upright in order to fill the ICS with liquid.
15. Place the refrigerant tank in the correct upright position upon the scale.
16. Next you will open the refrigerant tank.
17. You will need to zero the scale in order to determine how much refrigerant has been removed from the tank and put into the ICS. This will need to be done after the tank has been opened to allow refrigerant to fill the hoses for a more accurate measurement of how much refrigerant has been moved into the ICS.
18. Open the refrigerant flow valve.
19. Monitor the scale to determine how much refrigerant has left the tank.
20. Close the refrigerant flow valve when the correct reading has been achieved.
21. Close the refrigerant tank.
22. You can now remove all hoses from the refrigerant tank, oil injector, and refrigerant flow valve.
23. You have successfully charged the ICS with refrigerant.

Note: You may want to observe the level of refrigerant in the accumulator sight glass in order to determine if the correct amount of refrigerant was put into the ICS.

APPENDIX J - ADVANCED CALCULATION EQUATIONS

This appendix details the methods used to obtain the thermodynamic values displayed on the “Advanced Calculations” screen of the ICS GUI.

Assumptions: The liquid is a saturated liquid at the inlet of the cold plate. Therefore, the density (ρ) of the liquid refrigerant at the pump can be approximated.

$$\rho = 1167.50 \frac{\text{kg}}{\text{m}^3}$$

The pump is designed so that the control voltage is linearly proportional to the liquid volumetric flow rate. The volumetric flow (\dot{V}) rate is determined by Equation 1, where V_{pump} is the pump’s control voltage.

$$\dot{V} = 1.67 \times 10^{-8} \left[\frac{\left(\frac{\text{m}^3}{\text{s}} \right)}{\left(\frac{\text{mL}}{\text{min}} \right)} \right] \cdot \frac{V_{pump}}{5} \left[\frac{\left(\frac{\text{mL}}{\text{min}} \right)}{\text{V}} \right] \quad [1]$$

The mass flow rate (\dot{m}) is determined by Equation 2.

$$\dot{m} = \rho \dot{V} \quad [2]$$

At states 1, 3, and 4 (refer to Figure 1 for state identification), the liquid can be approximated as a saturated liquid. While it may be slightly sub-cooled in reality, the saturated enthalpy value is still a good approximation of the actual enthalpy value (for ICS operating conditions, at 5°C sub-cool, the error will not exceed 7%). Equation 3 is a best-fit quadratic expression of the saturated liquid enthalpy (h) of R134a in kJ/kg at temperature T . This equation is used to find the enthalpy at states 1, 3, and 4.

$$h_{1,3,4} = 0.005 \cdot T_{1,3,4}^2 + 1.1287 \cdot T_{1,3,4} + 202.2 \quad [3]$$

Since the ICS is not capable of measuring the quality of the 2-phase state after the cold plate (state 2), the heat added to the fluid over the cold plate must be known to calculate its enthalpy. The heat added to the fluid is assumed to be the heat-input by the heat source (\dot{Q}_{in}). It is important to note that this assumption is valid only when the system is operating at steady-state. The enthalpy of the R134a refrigerant at state 2 can then be estimated as shown in Equation 4.

$$h_2 = \frac{\dot{Q}_{in}}{\dot{m}} + h_1 \quad [4]$$

To determine the quality at the 2-phase state, the liquid saturation enthalpy at that state must be known. Equation 5 is used to find this saturation enthalpy ($h_{saturation}$), where T_2 is the temperature at that state.

$$h_{saturation} = 0.005 \cdot T_2^2 + 1.1287 \cdot T_2 + 202.2 \quad (5)$$

The quality of the refrigerant at the exit of the cold plate can be approximated as the quantity of the difference between the enthalpy at this state and the saturation enthalpy, divided by the latent enthalpy at this temperature. At ICS operating conditions, the latent enthalpy ranges from 165 kJ/kg to 175 kJ/kg. In the quality calculation, it will be assumed to be 170 kJ/kg. Equation 6 estimates the quality at state 2 (x_2).

$$x_2 = \frac{h_2 - h_{saturation}}{170 \frac{\text{kJ}}{\text{kg}}} \quad (6)$$

The entropy values for the R-134a refrigerant are found using a method similar to that used to find the enthalpy. Again, the refrigerant was approximated as a saturated liquid at states 1, 3, and 4. To find the entropy at states 1, 3, and 4, as well as the saturated-liquid entropy at state 2, a cubic best-fit equation was developed, and is shown as Equation 7.

$$s_{1,saturation,3,4} = -1.915 \times 10^{-9} \cdot T_{1,2,3,4}^3 + 2.084 \times 10^{-5} \cdot T_{1,2,3,4}^2 + 4.014 \times 10^{-5} \cdot T_{1,2,3,4} + 1.585 \quad (7)$$

To find the entropy at the 2-phase state, the latent entropy must be assumed. For the ICS operating conditions, the latent entropy ranges from 0.53 [kJ/kg-K] to 0.58 [kJ/kg-K]. For the state 2 entropy calculation, it will be assumed to be 0.555 [kJ/kg-K]. The entropy at state 2 is then approximated by Equation 8.

$$s_2 = 0.555 \frac{\text{kJ}}{\text{kg-K}} \cdot x_2 + s_{saturation} \quad (8)$$

*Note – These methods yield accurate approximations ONLY when the system has reached steady state.